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Electrical Engineering Research Laboratory
The University of Texas

Some Meteorological and Oceanographic Characteristics of the Golden Gate California Area

By

K. H. Jehn
J. R. Gerhardt
D. F. Metcalf
S. J. Prosser

26 February 1954

Prepared under U. S. Navy Contract NOrd 9195
Problem Statement UTX-1-CC-9

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SOME METEOROLOGICAL AND OCEANOGRAPHIC CHARACTERISTICS OF THE GOLDEN GATE CALIFORNIA AREA

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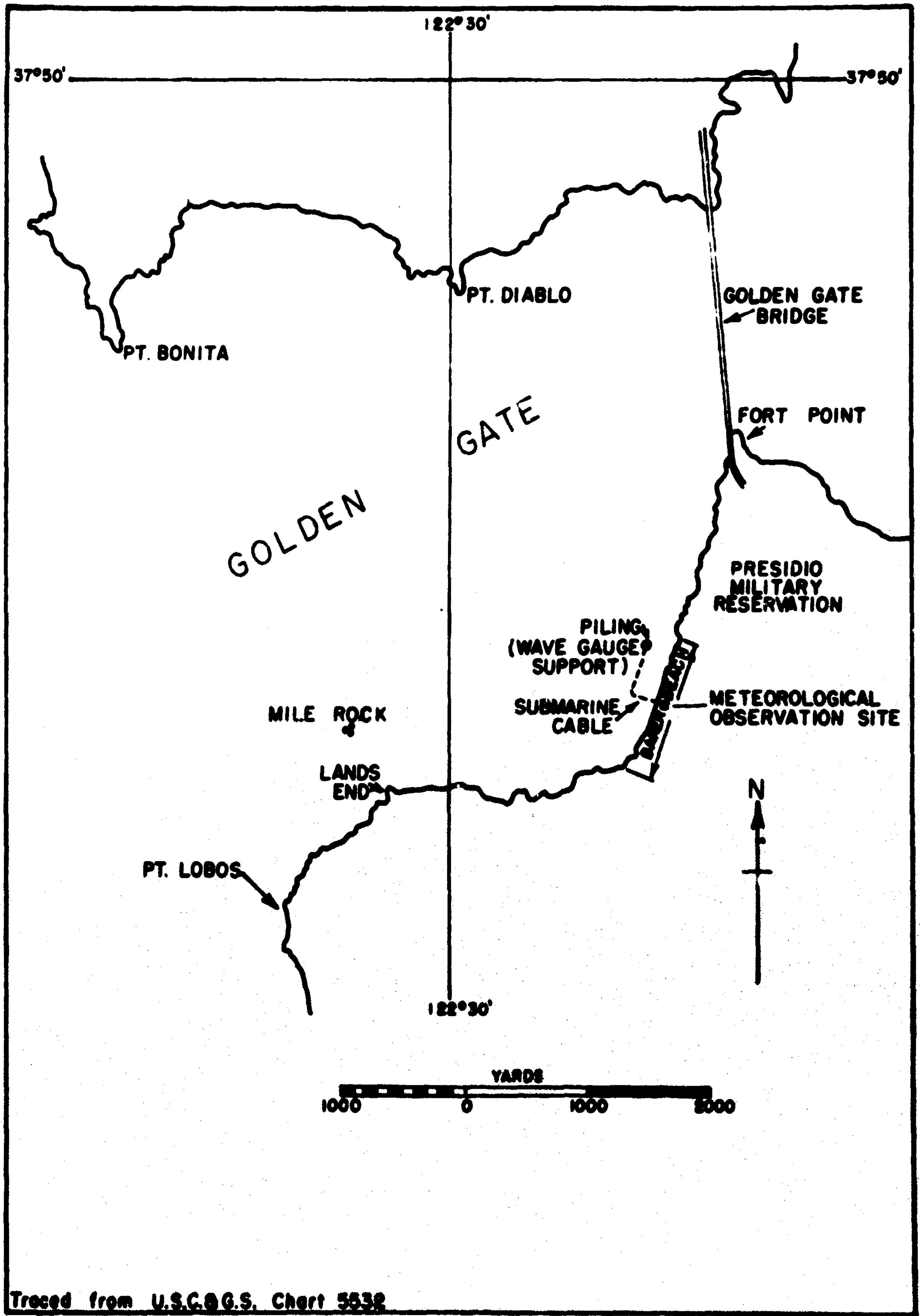
ABSTRACT

A series of low-level temperature and moisture soundings taken on the southern shore of the Golden Gate channel during April, 1953 in connection with certain microwave propagation tests are analyzed to determine the refractive index gradients in the first few hundred feet above the channel. While most of the soundings show the essentially uniform standard gradients to be expected in an air mass having a long overwater trajectory and compare favorably with the existing Oakland, California radiosonde observations, certain smaller scale features involving elevated substandard layers and sea breeze ducts are occasionally found which cannot be correlated with larger scale surface or upper air weather data. A second phase of the report consists of the analysis of a series of wave gage recordings of the water surface. Characteristic wave amplitudes and periods are determined and comparisons are made between amplitude values obtained from several types of wave sensing elements. The rather complex oceanographic features of the channel appear to be at least partially responsible for such effects as, 1) an observed average $H_{1/3}$ / H_{max} ratio of about 1.5 as compared to reported values of about 1.85, 2) an approximate two-fold increase in the characteristic period of the waves over the period from 13-14 April, and 3) an infrequent but well-marked surge-type period of some 2-3 minutes in the wave recordings. Surface wave patterns computed from subsurface pressure type gages are significantly lower than step gage values and confirm required average correction factors previously reported as ranging from 1.1 to 1.35. A number of analyses are made using the amplitude probability method of data reduction to $H_{1/3}$ values and it is concluded that this method is more accurate than that involving a direct computation of the average of the highest one-third waves from the original record.

I. INTRODUCTION

During the period from late January through April, 1953 personnel of this laboratory conducted certain microwave radio propagation tests off the California coast near San Francisco, with the test area located seaward from the Golden Gate Bridge (Figure 1). In connection with these tests certain basic meteorological



OUTLINE MAP OF GOLDEN GATE AREA
FIGURE 1

EERL 1469

and oceanographic data were obtained. Measurements of air temperature and moisture were made in the vicinity of the radio paths, yielding refractive index profiles up to several hundred feet above the sea surface. The state of the sea surface was also carefully determined by using three different wave measuring instruments mounted on a steel piling located off Baker Beach.

The principal objectives of this report are to describe the meteorological and oceanographic observation and measurement programs and to present some of the meteorological and oceanographic findings for the test area during April, 1953.

II. OBSERVATIONAL PROGRAM

A. Meteorology.

The basic meteorological observations were those made by means of barrage balloon soundings to heights in the order of 500 feet in the Baker Beach area (Figure 2), using the Electrical Engineering Research Laboratory artificially ventilated wet-and dry-bulb psychrograph as a sensing element. A few more detailed observations were made in the first 25 feet above the water on the piling. Soundings were made once and sometimes twice a day, at times when the wind direction made possible a sounding as nearly representative as possible of the radio path across the Golden Gate inlet. In addition, many check measurements of air temperature and humidity were made with a standard U. S. Weather Bureau type sling psychrometer at points near the balloon reel and at the water's edge on Baker Beach.

A few helicopter soundings of temperature and moisture were made overwater in the test area, using craft made available through the courtesy of the Presidio of San Francisco. Based on the soundings actually obtained, and in the light of Randall's studies [7], it is quite likely that the helicopter could be a useful adjunct to a measurement program of this kind but more field experience is needed before any definite statement can be made. It is fair to say, however, that the helicopter flights at San Francisco were generally not successful enough to justify the trouble of installing the equipment which had to be done for each flight. Among the operational difficulties encountered were those concerned with advance scheduling of each flight, availability of a craft at the time desired, and the variation in local weather conditions.

Additional frequent meteorological observations were made both at the meteorological site and the piling. These were both visual and instrumental, and included such items as the aforementioned temperature and wet-bulb temperature as well as sky condition, visibility, wind direction and speed, and water temperature. Wind direction was indicated by direct visual observation of a wind vane mounted near the observation truck about five feet above ground. Representative directions were those from SSW through North, approximately (see Figure 1). Wind

METEOROLOGICAL SOUNDING SITE, BAKER BEACH AREA, LOOKING TOWARD POINT DIABLO.

FIGURE 2

speed was measured at the piling with a conventional 3-cup rotation anemometer (Signal Corps World War II model, bakelite cups, magneto head) whose output was placed on an Esterline-Angus 0-1 m.a. recorder in the truck shown in Figure 2.* Wind records are available from 0800 PST 3 April 1953 through 29 April; the anemometer was removed from the piling at 0815 PST 28 April, and set up temporarily at the Baker Beach meteorological site beginning 1045 PST 28 April 1953. Both fast speed (3" per minute) and slow speed (3" per hour) wind records were obtained, with an effort made to record wind at fast paper speed when wave records were being made. The wind record was made virtually continuous by running the recording meter at slow speed between runs and over nights and Sundays.

The water temperature measurements were made with a mercurial thermometer having a small bucket attachment at the bulb end. Observations were made generally once per day off the rocks opposite the piling about 1500 feet north of the meteorological site, and as often from the piling as trips were made for servicing the equipment.

Standard U. S. Weather Bureau teletype weather reports for stations in the vicinity, including both surface and upper air observations, were collected and made available through the courtesy of the Official-in-Charge, U. S. Weather Bureau, San Francisco Airport.

Sea water temperatures, measured each two hours at the light ship "San Francisco" (WAL-612), located between Golden Gate and Southeast Farallon Island, as well as wave direction and period, were made available through the courtesy of the U. S. Coast Guard.

Finally, in an effort to determine certain smaller scale atmospheric features representative of the overwater path, a number of observations were made of the simultaneous fluctuations of air temperature and index of refraction at microwave frequencies with the Crain refractometer [2] using a shore-based site some 50 feet above and 250 feet from the water. Unfortunately the combination of the large differential in surface radiational heating and cooling of sand over water and the spray and salt particles thrown into the atmosphere by the breaking surf introduced temperature and refractive index variations that were not representative of overwater conditions. While the more or less general on-shore winds permitted representative measurements of overwater temperature and moisture gradients with the balloon-borne land-based psychrograph at altitudes above some height of the order of 100 feet, these same on-shore winds significantly increased the likelihood of atmospheric contamination by surf action.

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*All EERL recording meters were housed in the same truck.

B. Oceanography.

Among the measurements to be synchronized with the radio data were those characterizing the sea surface from which radio waves were being reflected. The approach to this problem was to provide numerous data representative of the sea surface on the radio path, such that statistical analysis of the results would be feasible. Photographs, taken from various vantage points, were used in an effort to establish qualitatively the character of the sea surface and the essential areal representivity of point measurements of ocean wave heights and periods. The point measurements were made by means of three different wave gages, all mounted on a supporting platform in the form of a steel piling, driven into the ocean floor about 200 yards off Baker Beach (Figures 1 and 2) at a point where the water depth was some 35-40 feet.

The wave gages were all mounted on the seaward side of the piling about 2½ feet from the structure. Access to the piling was gained by a ladder mounted on the northeast side, and upper and lower platforms made possible servicing of the equipment (Figure 3). Wave heights and periods were measured by three different instruments, a step gage, a pressure gage and a continuous-wire gage. The step gage [1], described in Appendix B, utilized as sensing elements spark plugs spaced 0.2 feet apart along 14 feet of the stainless steel supporting pipe. The instrument was raised and lowered for servicing by means of a small A-frame mounted on the upper platform. A Mark IX pressure gage [8] was mounted on the steel pipe of the step gage as support, two feet below the lowest spark plug and approximately 30 feet from the ocean floor. This gage measured variations in the weight of water above it by means of a differential pressure potentiometer of conventional pattern and was made available on loan from the University of California Wave Research Laboratory. A continuous-wire gage was composed of three stainless steel wires and was arranged vertically on mounting brackets adjacent to the step gage.* One wire was used to measure the position of the water surface by the electrical resistance of the exposed portion; the other two, in conjunction with the third, yielded the instantaneous slope of the water surface. With the wires positioned at the vertices of a right triangle, components of the slope in two directions were obtained. Further details on this gage appear in Appendix A.

An effort was made to obtain tide variations at the piling by placing the step gage output on an Esterline-Angus recorder, operated at a paper speed of 3 inches per hour, and with a designed sensitivity of 14 feet for full scale (0-1 m.a.). The calibration resistor scheme was based on the performance of the

---

*Step and pressure gages in Figure 3 are in servicing position. The continuous-wire gage was removed following a picket boat collision on 17 April and is not shown in the photograph. The pressure gage may be seen fastened near the end of the step gage pipe.

WAVE – GAUGE PILING OFF BAKER BEACH,
LOOKING TOWARD BAKER BEACH.

FIGURE 3

step gage in salt water (30% salinity), but did not take into account the extra-long submarine cable (2300 feet) between piling and recording meter. Briefly stated, the tide gage output in the field became compressed to something in the order of one-half of full scale and this factor together with the considerable amount of calibration drift of the tide gage experienced during the period of observations, made the record very difficult to evaluate. Tide figures obtained from the step gage, however, compared favorably with those of the observed tide at Golden Gate.

III. PRESENTATION OF DATA AND ANALYSES

A. Meteorological Findings.

1. Refractive Index Profiles. The dry-bulb and wet-bulb temperature soundings were plotted on height coordinates as shown in Figures 4 through 18, along with derived values of vapor pressure and refractive index. In order to minimize the effect of the occasionally large and more or less random moisture fluctuations normally encountered in overwater observations, the refractive index and vapor pressure values were also computed and resultant profiles sketched from smoothed dry-bulb and wet-bulb temperature gradients. These values are all indicated by crosses on the above figures. The soundings illustrated in Figures 4-18 include all but a few of the complete list of soundings given in Table 1. Those not shown represent measurements which were either essentially duplicates of those taken earlier or later of the same day or which were of little value due to equipment malfunctioning.

For the most part the refractive index gradients were uniform to the top of the sounding and for 10 of the 15 days represented by the figures showed essentially standard or slightly substandard gradients. There is also fairly reliable evidence from sea surface measurements and occasional sling psychrometer and low level piling soundings of the existence of a shallow duct in the first 10-20 feet above the water. Both of these features are in general agreement with the type of refractive index sounding one would expect to find from an overwater sounding in a marine air mass. For the most part, too, psychrograph soundings showing a uniform index-of-refraction gradient agreed fairly well with values determined from the Oakland radiosonde in spite of the non-conformity in time and distance between the two. Figure 14, for example, representing data taken in the afternoon of April 23, shows a near standard profile for both the psychrograph and radiosonde data. Where there is a discrepancy, it appears that the psychrograph refractive index profile tends to be somewhat more substandard than that derived from the radiosonde. Reference can be made here to Figures 5 (7 April), 9 (14 April), 15 (24 April) and 16 (25 April). It may be that the shallower and warmer San Francisco Bay waters off Oakland give rise to a greater index gradient there than immediately off the deep water inlet, but there is too great a discrepancy between the scale distance and time of the two measurements to make any definite statements.

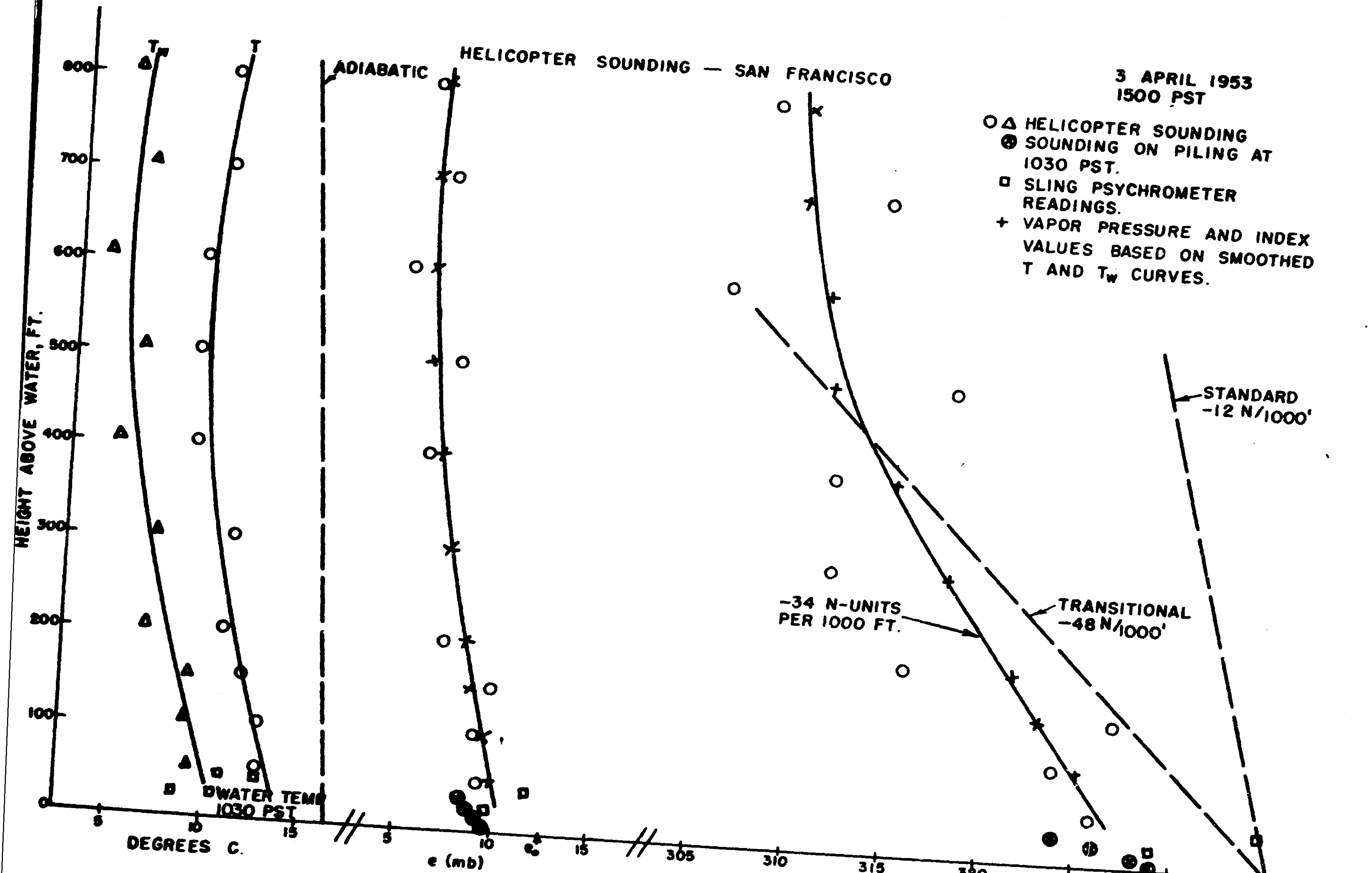

HELICOPTER SOUNDING — SAN FRANCISCO
3 APRIL 1953
1500 PST
○ △ HELICOPTER SOUNDING
⊛ SOUNDING ON PILING AT 1030 PST.
□ SLING PSYCHROMETER READINGS.
+ VAPOR PRESSURE AND INDEX VALUES BASED ON SMOOTHED T AND T_w CURVES.
HEIGHT ABOVE WATER, FT.
0
100
200
300
400
500
600
700
800
T_w
T
ADIABATIC
WATER TEMP 1030 PST
DEGREES C.
5
10
15
e (mb)
e_o
305
310
315
320
325
330
335
N - UNITS
N_o = 343
STANDARD -12 N/1000'
TRANSITIONAL -48 N/1000'
-34 N-UNITS PER 1000 FT.

FIGURE 4

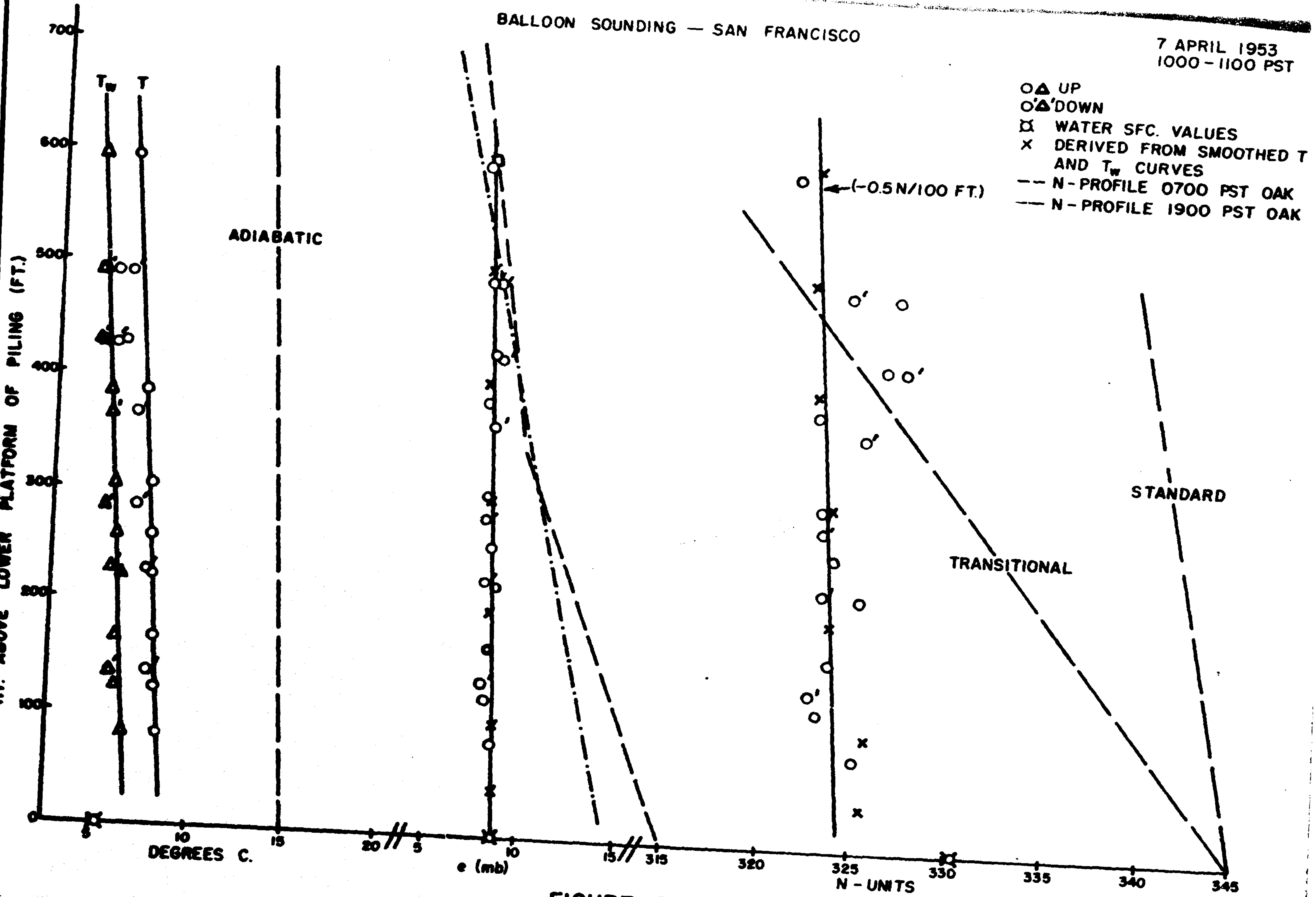

BALLOON SOUNDING — SAN FRANCISCO
7 APRIL 1953
1000 - 1100 PST
O△ UP
O'△' DOWN
WATER SFC. VALUES
X DERIVED FROM SMOOTHED T AND T_w CURVES
N-PROFILE 0700 PST OAK
N-PROFILE 1900 PST OAK
(-0.5 N/100 FT.)
ADIABATIC
STANDARD
TRANSITIONAL
HT. ABOVE LOWER PLATFORM OF PILING (FT.)
T_w
T
DEGREES C.
e (mb)
N - UNITS

FIGURE 5

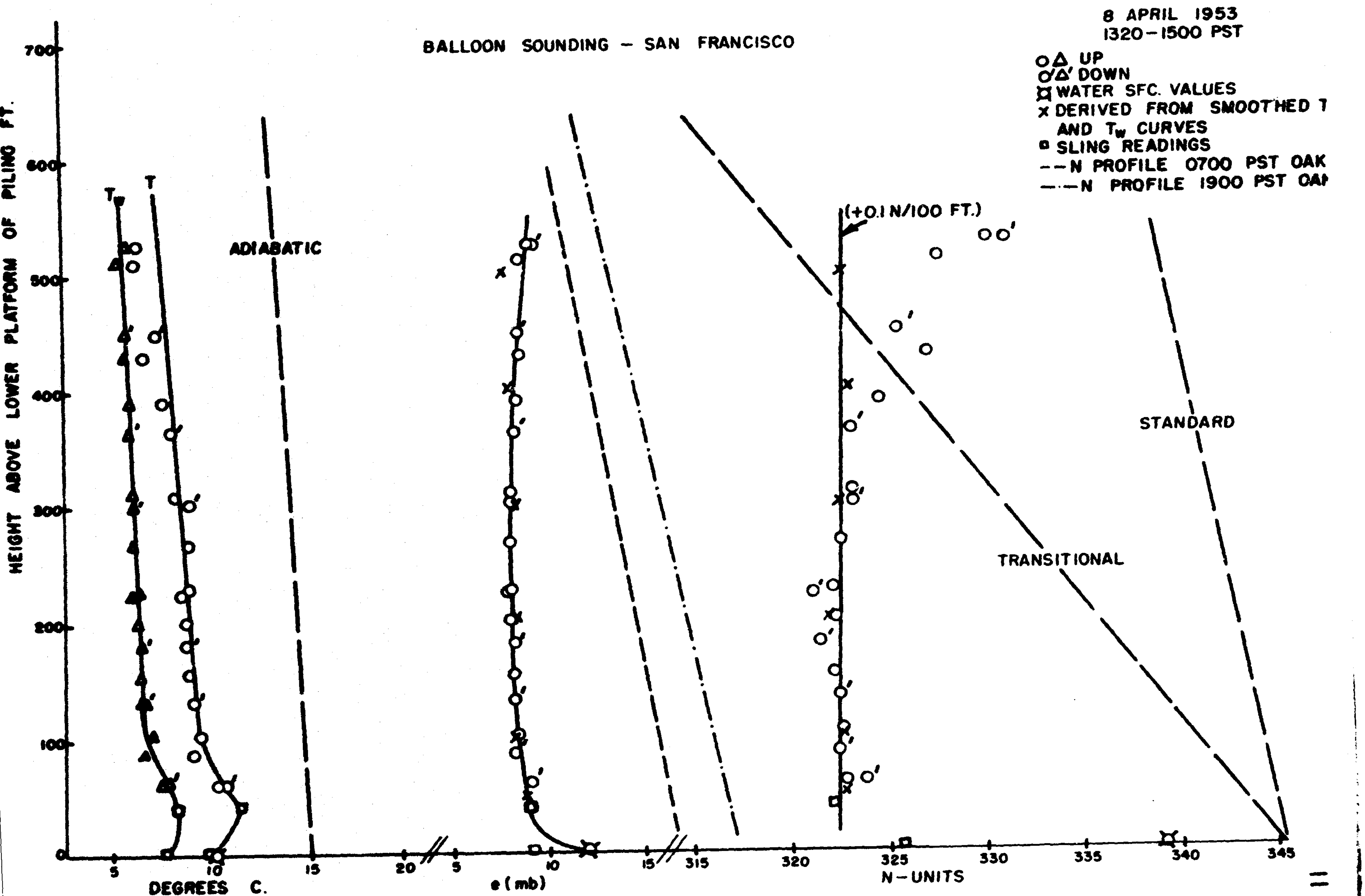
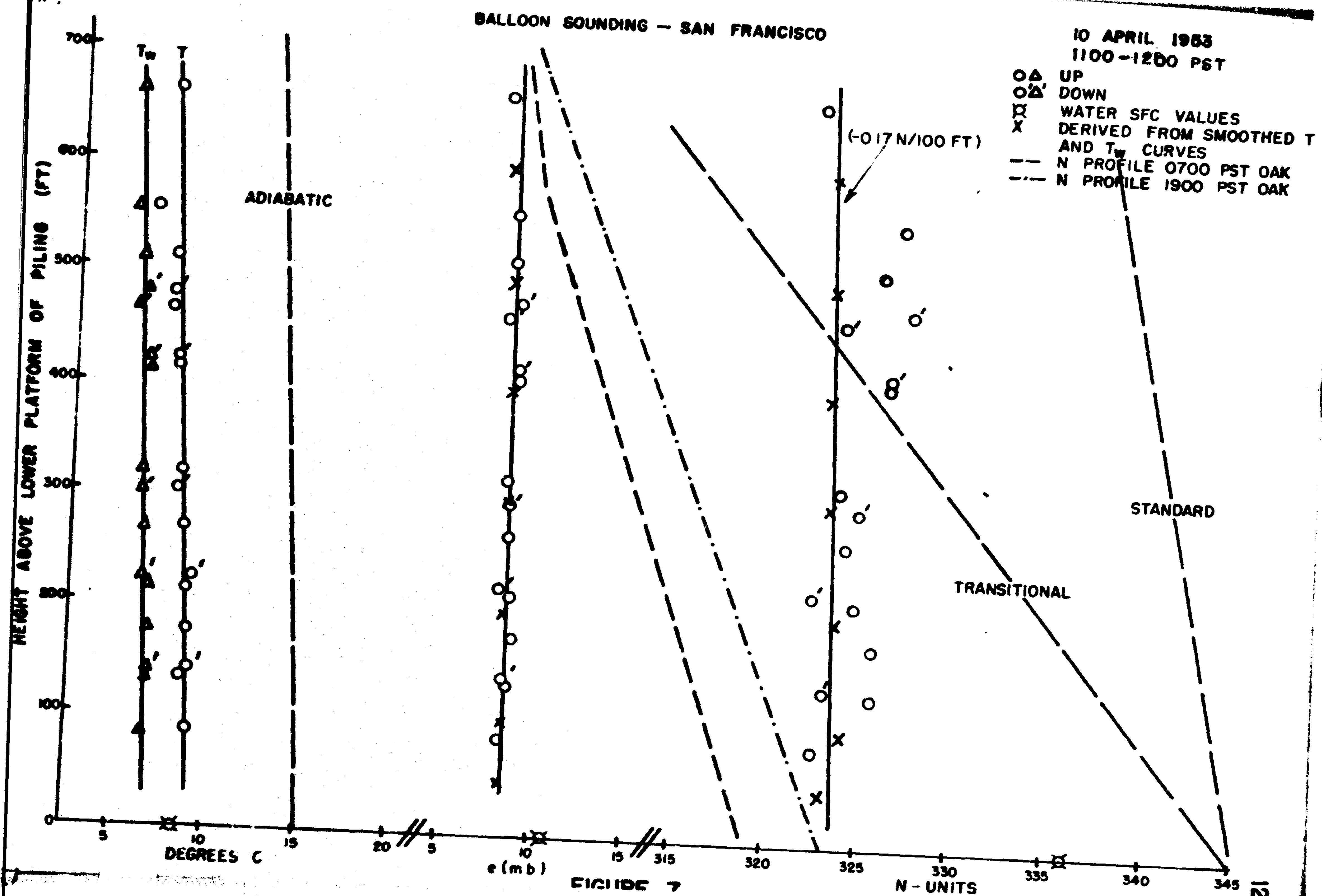
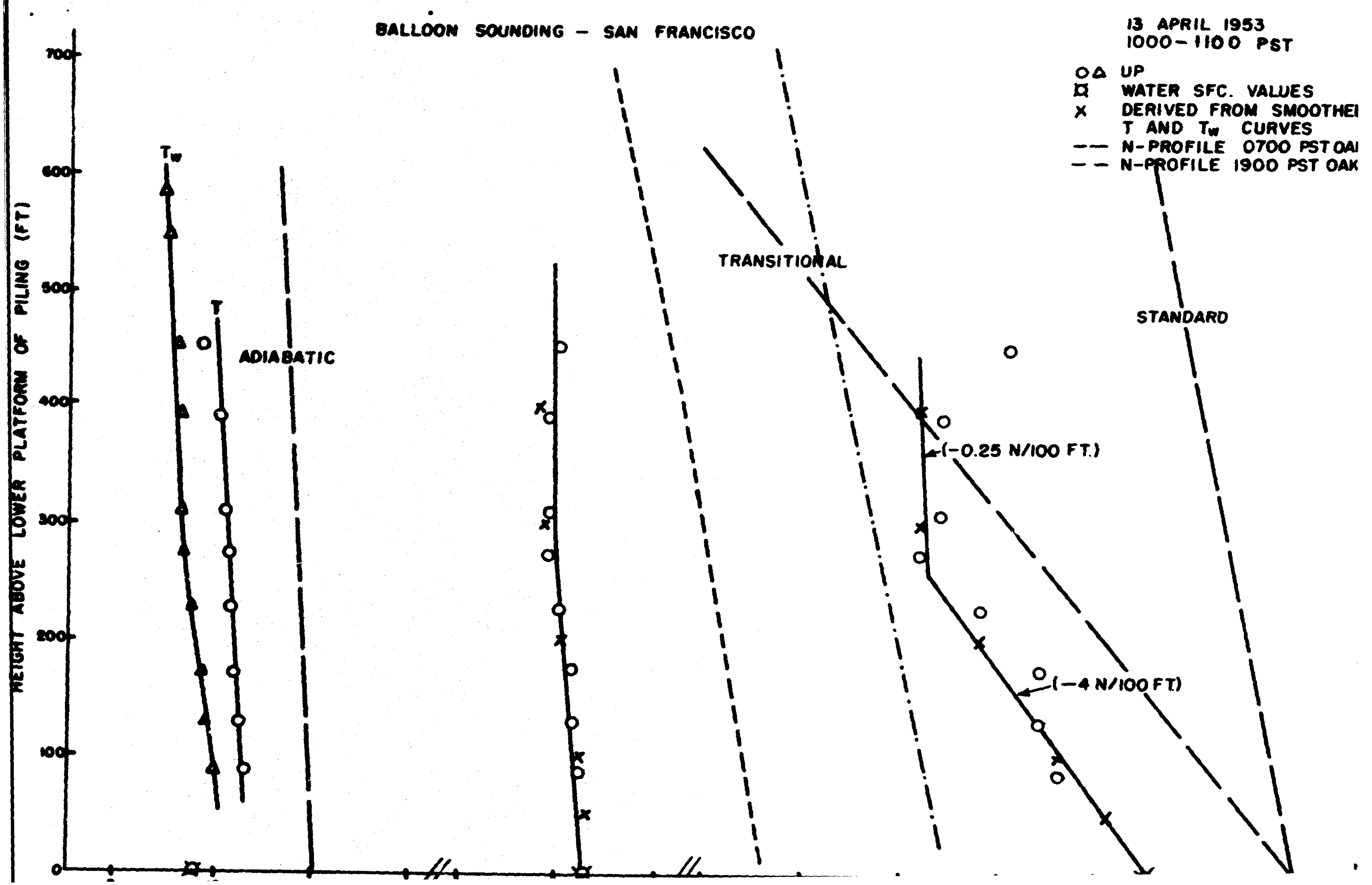

BALLOON SOUNDING – SAN FRANCISCO
8 APRIL 1953
1320–1500 PST
○△ UP
○'/△' DOWN
WATER SFC. VALUES
x DERIVED FROM SMOOTHED T AND T_w CURVES
SLING READINGS
– – N PROFILE 0700 PST OAK
–·– N PROFILE 1900 PST OAK
HEIGHT ABOVE LOWER PLATFORM OF PILING FT.
ADIABATIC
T_w
T
(+0.1 N/100 FT.)
STANDARD
TRANSITIONAL
DEGREES C.
e (mb)
N–UNITS

FIGURE 6

FIGURE 6


BALLOON SOUNDING — SAN FRANCISCO
10 APRIL 1953
1100-1200 PST
UP
DOWN
WATER SFC VALUES
DERIVED FROM SMOOTHED T AND T_w CURVES
N PROFILE 0700 PST OAK
N PROFILE 1900 PST OAK
(-0.17 N/100 FT)
ADIABATIC
STANDARD
TRANSITIONAL
T_w
T
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT)
700
600
500
400
300
200
100
0
5
10
15
20
DEGREES C
5
10
15
e (mb)
315
320
325
330
335
340
345
N - UNITS



BALLOON SOUNDING — SAN FRANCISCO
13 APRIL 1953
1000–1100 PST
○△ UP
WATER SFC. VALUES
× DERIVED FROM SMOOTHED T AND T_W CURVES
N-PROFILE 0700 PST OAK
N-PROFILE 1900 PST OAK
T_W
T
ADIABATIC
TRANSITIONAL
STANDARD
(−0.25 N/100 FT.)
(−4 N/100 FT.)
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT)
0
100
200
300
400
500
600
700

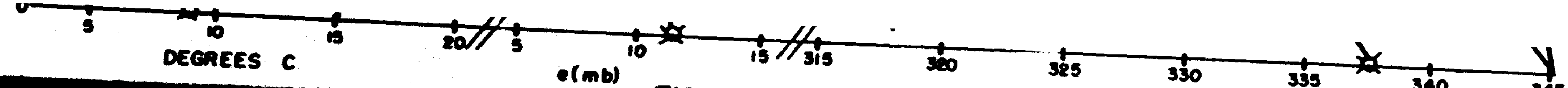


FIGURE 8

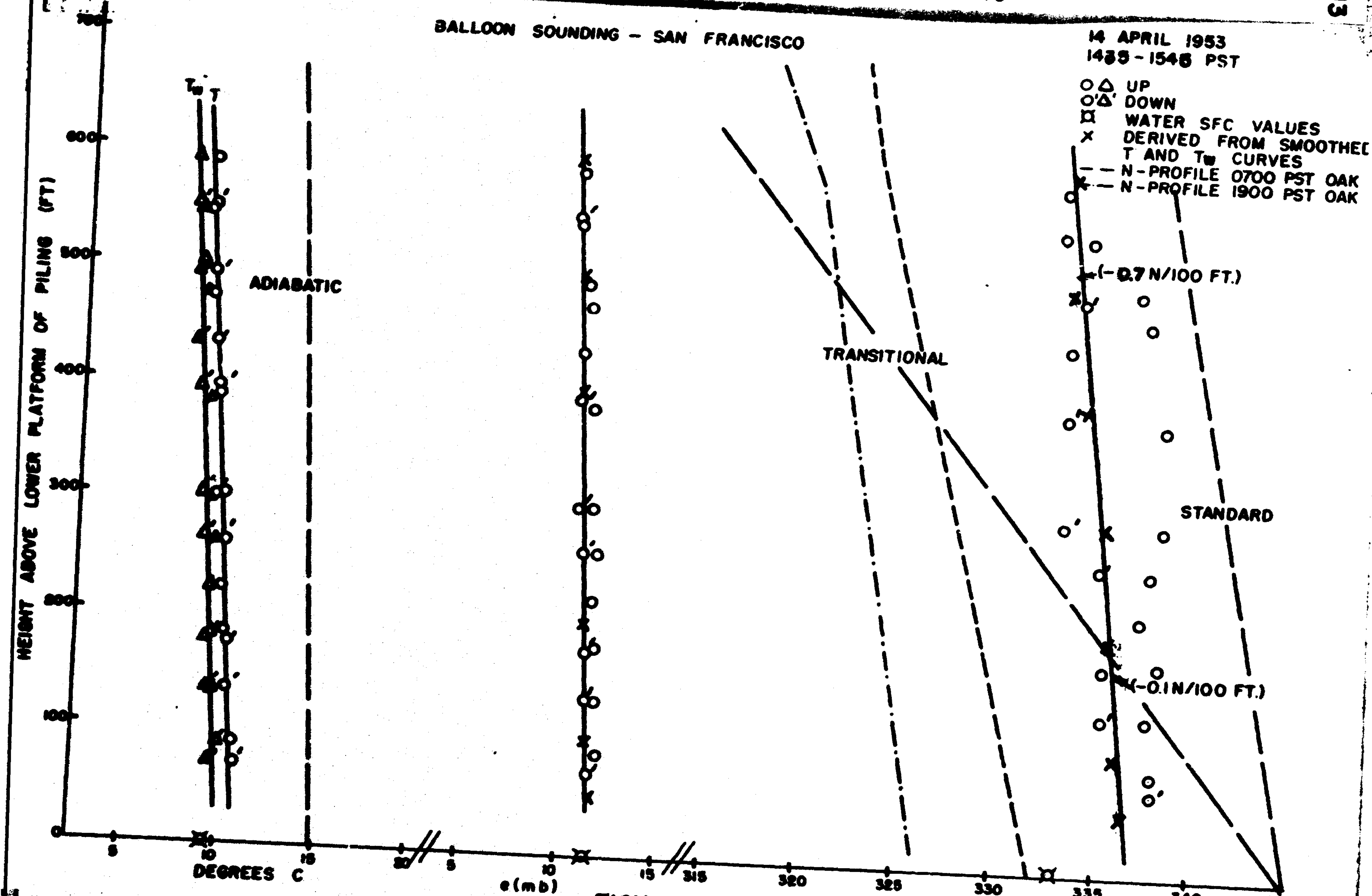
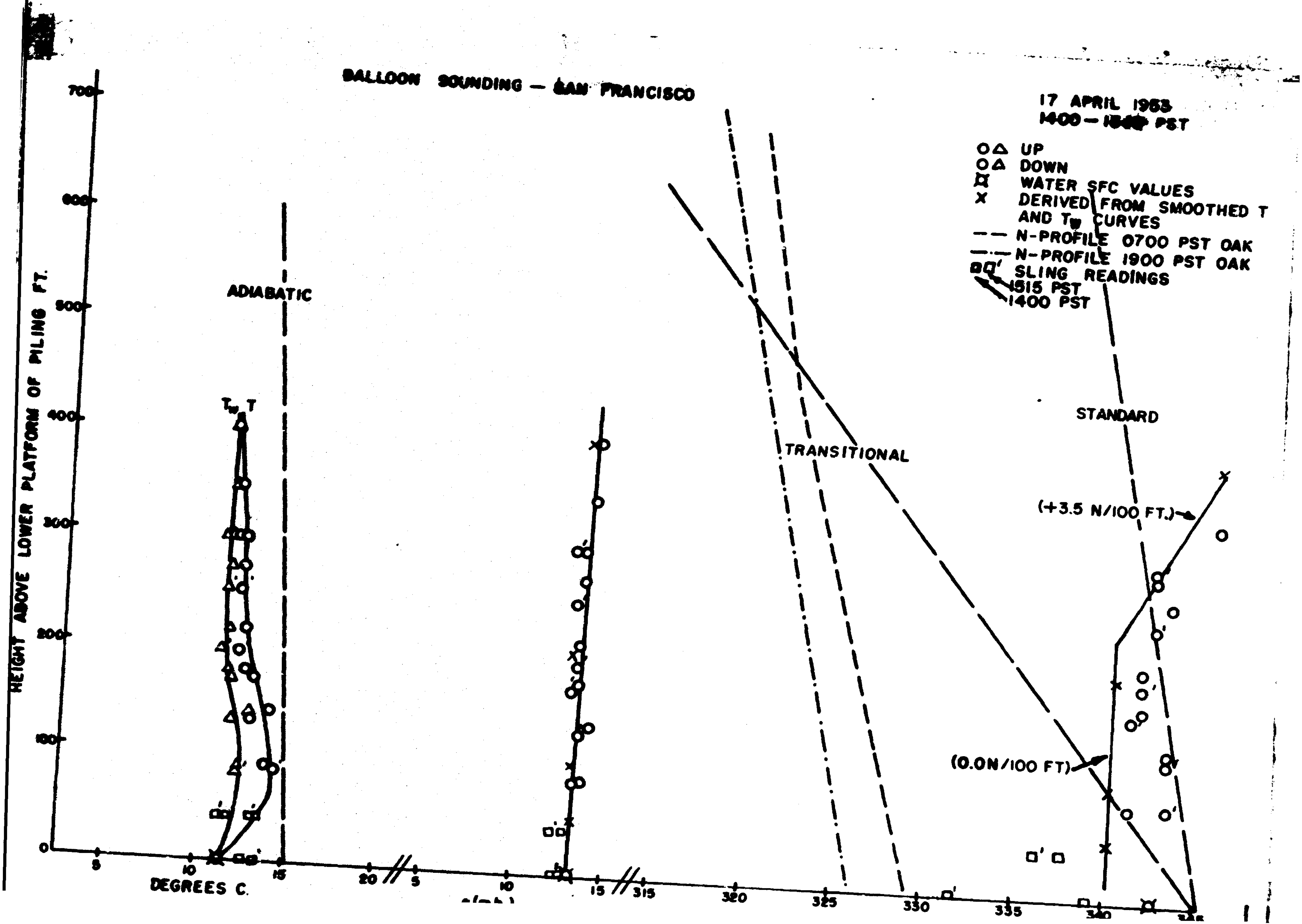


FIGURE 9


BALLOON SOUNDING — SAN FRANCISCO
17 APRIL 1953
1400 — PST
UP
DOWN
WATER SFC VALUES
DERIVED FROM SMOOTHED T AND T_w CURVES
N-PROFILE 0700 PST OAK
N-PROFILE 1900 PST OAK
SLING READINGS
1515 PST
1400 PST
ADIABATIC
TRANSITIONAL
STANDARD
T_w
T
(+3.5 N/100 FT.)
(0.0N/100 FT)
HEIGHT ABOVE LOWER PLATFORM OF PILING FT.
DEGREES C.
0
100
200
300
400
500
600
700
5
10
15
20
5
10
15
315
320
325
330
335
340

DEGREES C. e(mb) N-UNITS

FIGURE 10

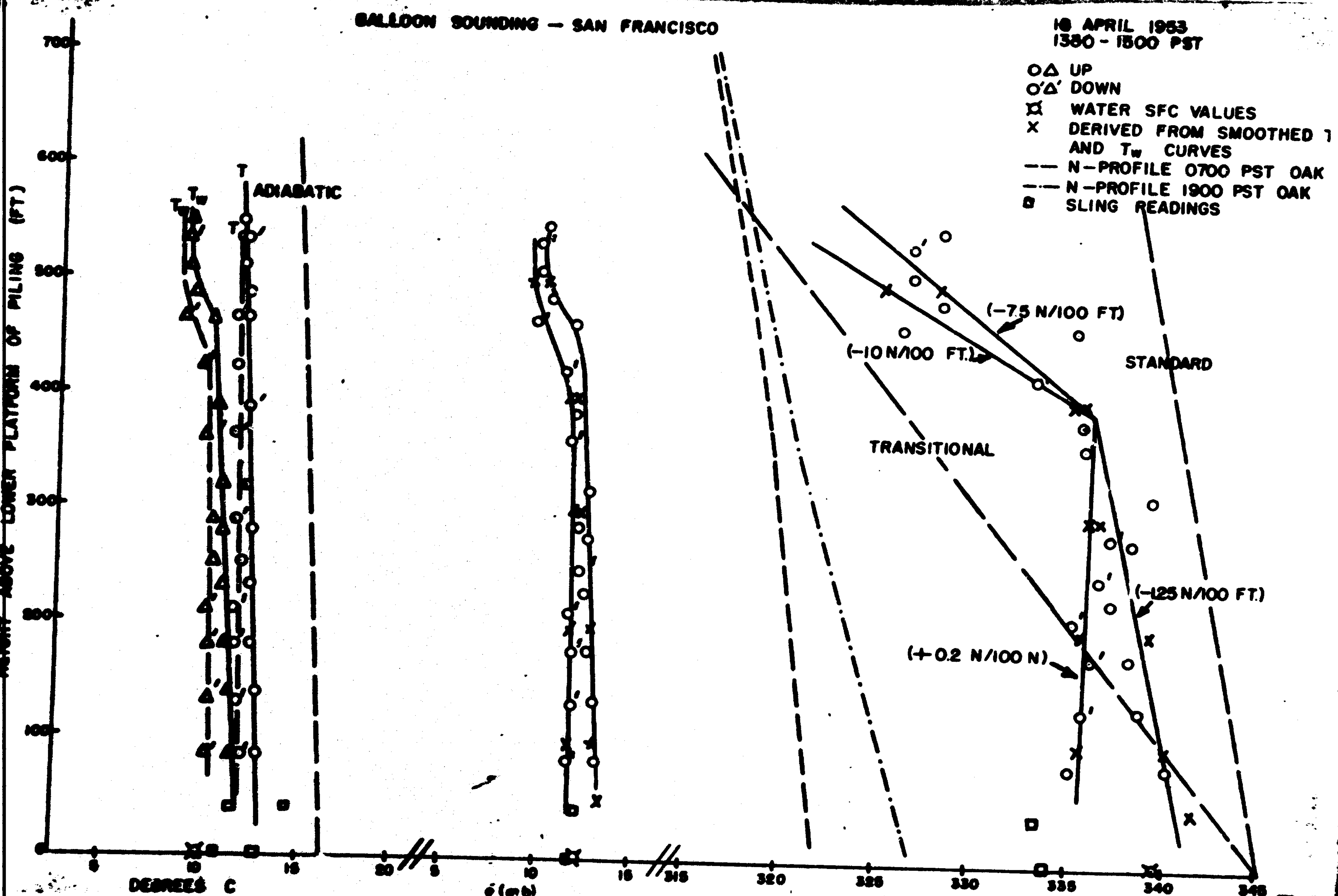


FIGURE 11

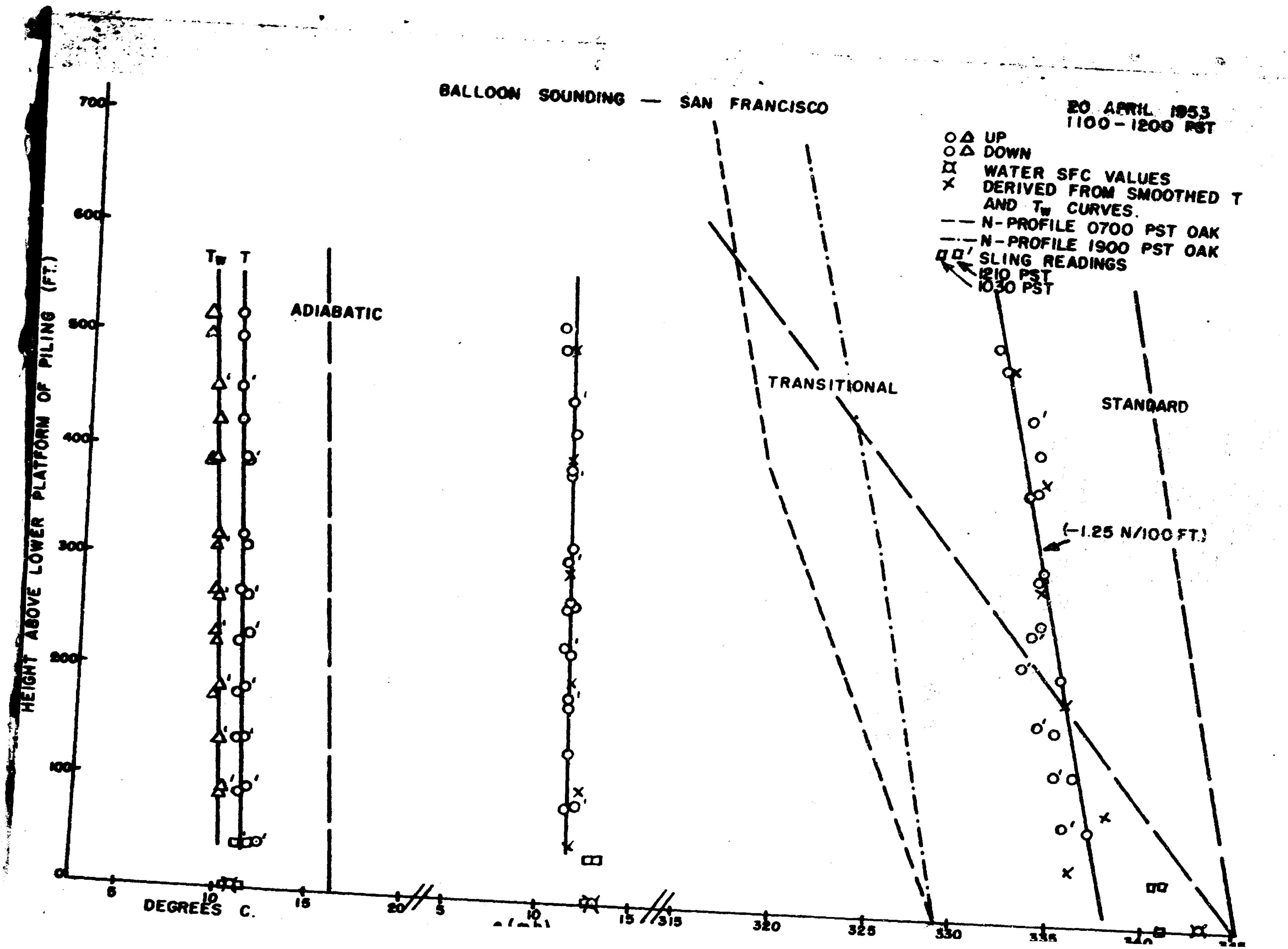

BALLOON SOUNDING — SAN FRANCISCO
20 APRIL 1953
1100 - 1200 PST
UP
DOWN
WATER SFC VALUES
DERIVED FROM SMOOTHED T AND T_W CURVES.
N-PROFILE 0700 PST OAK
N-PROFILE 1900 PST OAK
SLING READINGS
1210 PST
1030 PST
T_W
T
ADIABATIC
TRANSITIONAL
STANDARD
(-1.25 N/100 FT.)
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT.)
DEGREES C.
0
100
200
300
400
500
600
700
5
10
15
20
5
10
15
315
320
325
330
335
340

FIGURE 12

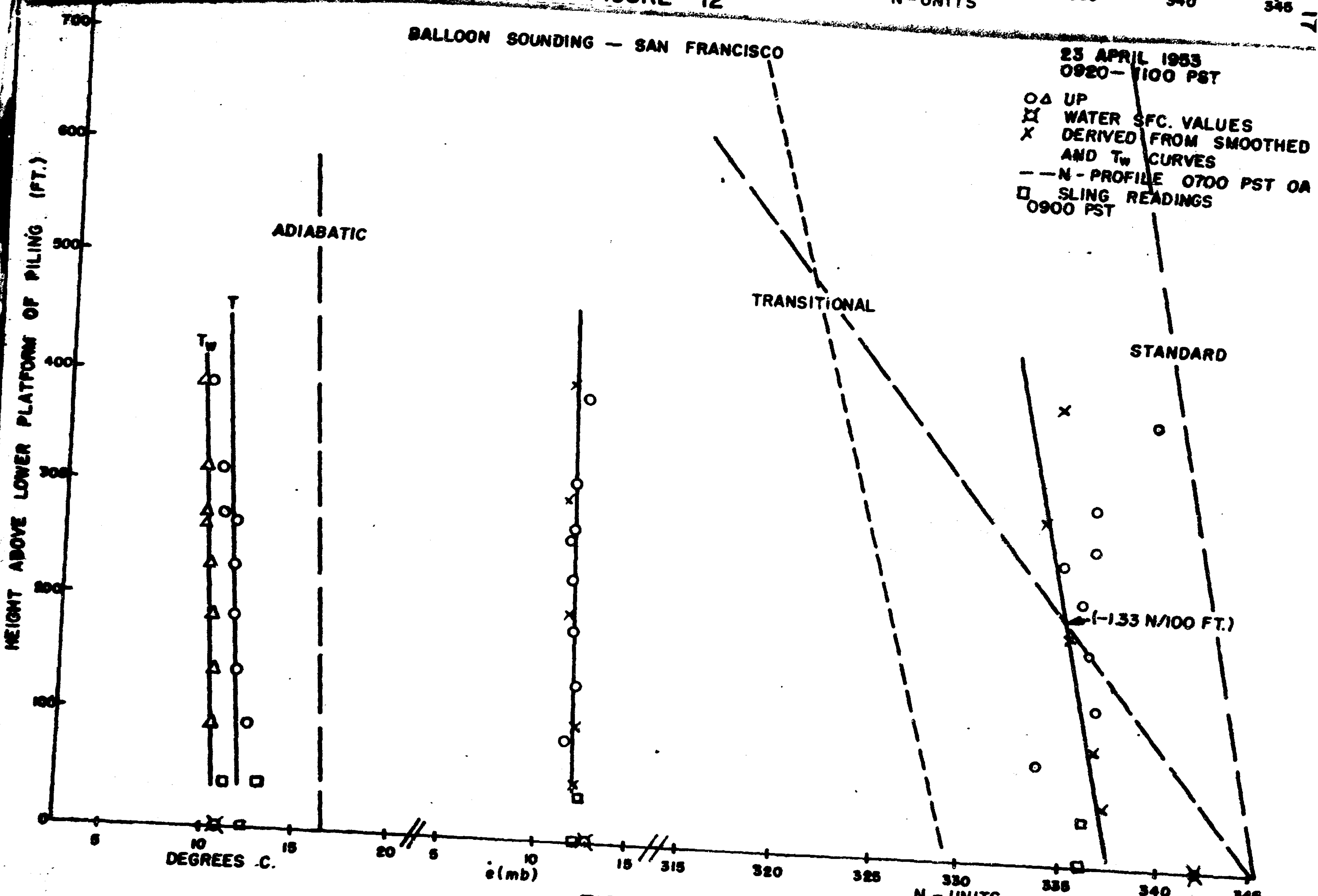


FIGURE 13

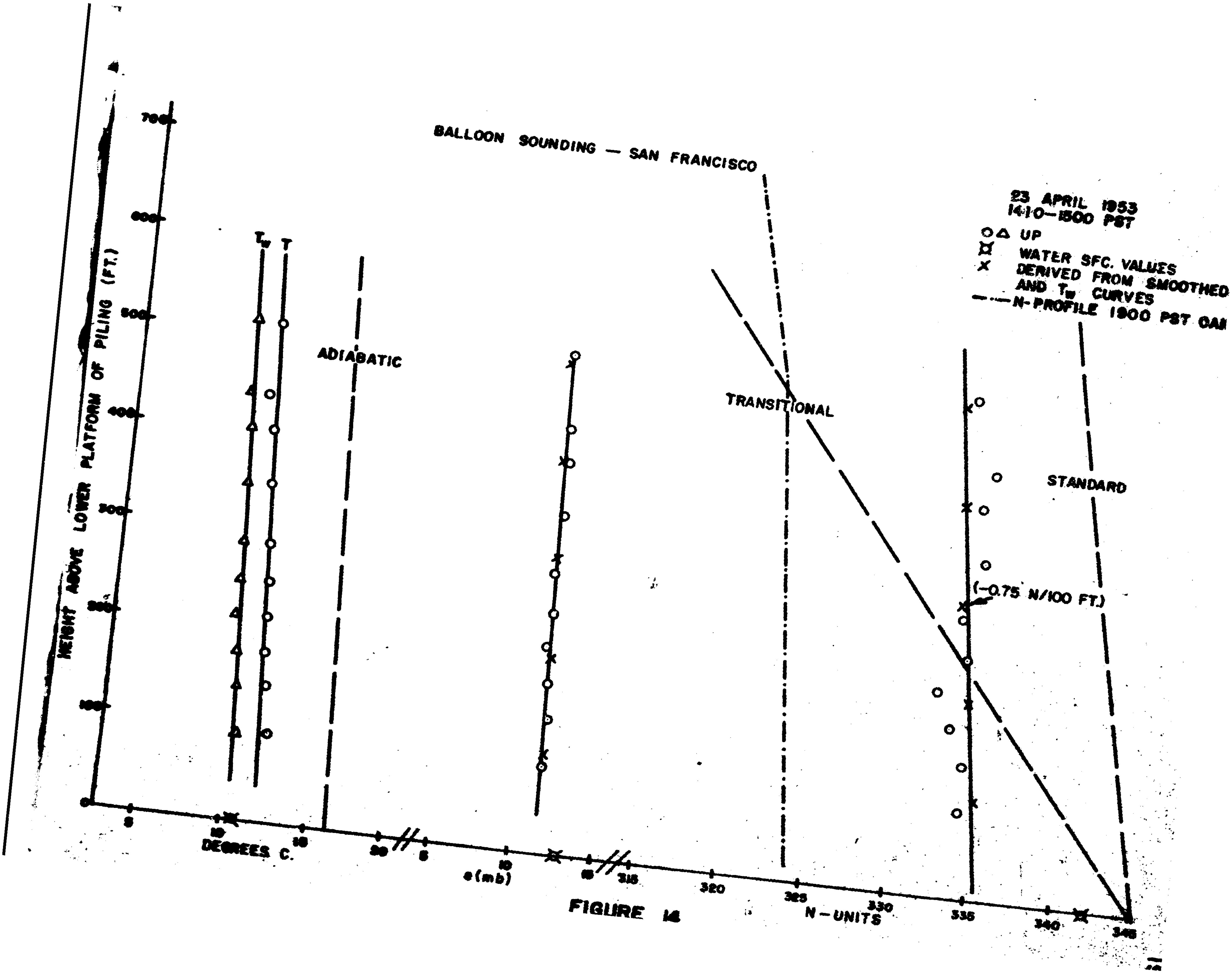

BALLOON SOUNDING — SAN FRANCISCO
23 APRIL 1953
1410–1500 PST
○ △ UP
WATER SFC. VALUES
× DERIVED FROM SMOOTHED
AND T_w CURVES
N-PROFILE 1900 PST OAK
ADIABATIC
TRANSITIONAL
STANDARD
(−0.75 N/100 FT.)
T_w
T
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT.)
DEGREES C.
e(mb)
N-UNITS

FIGURE 14

FIGURE 14

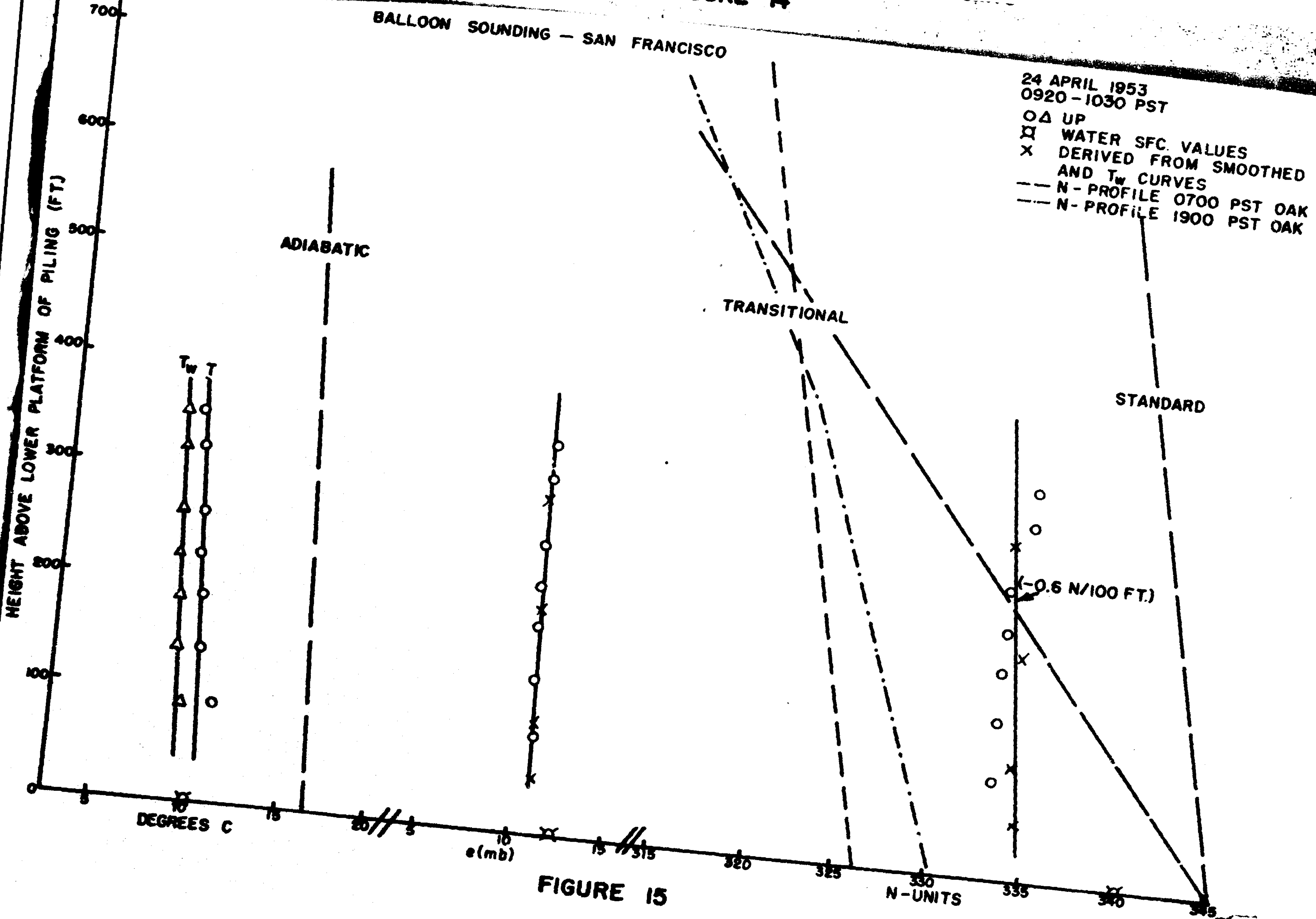
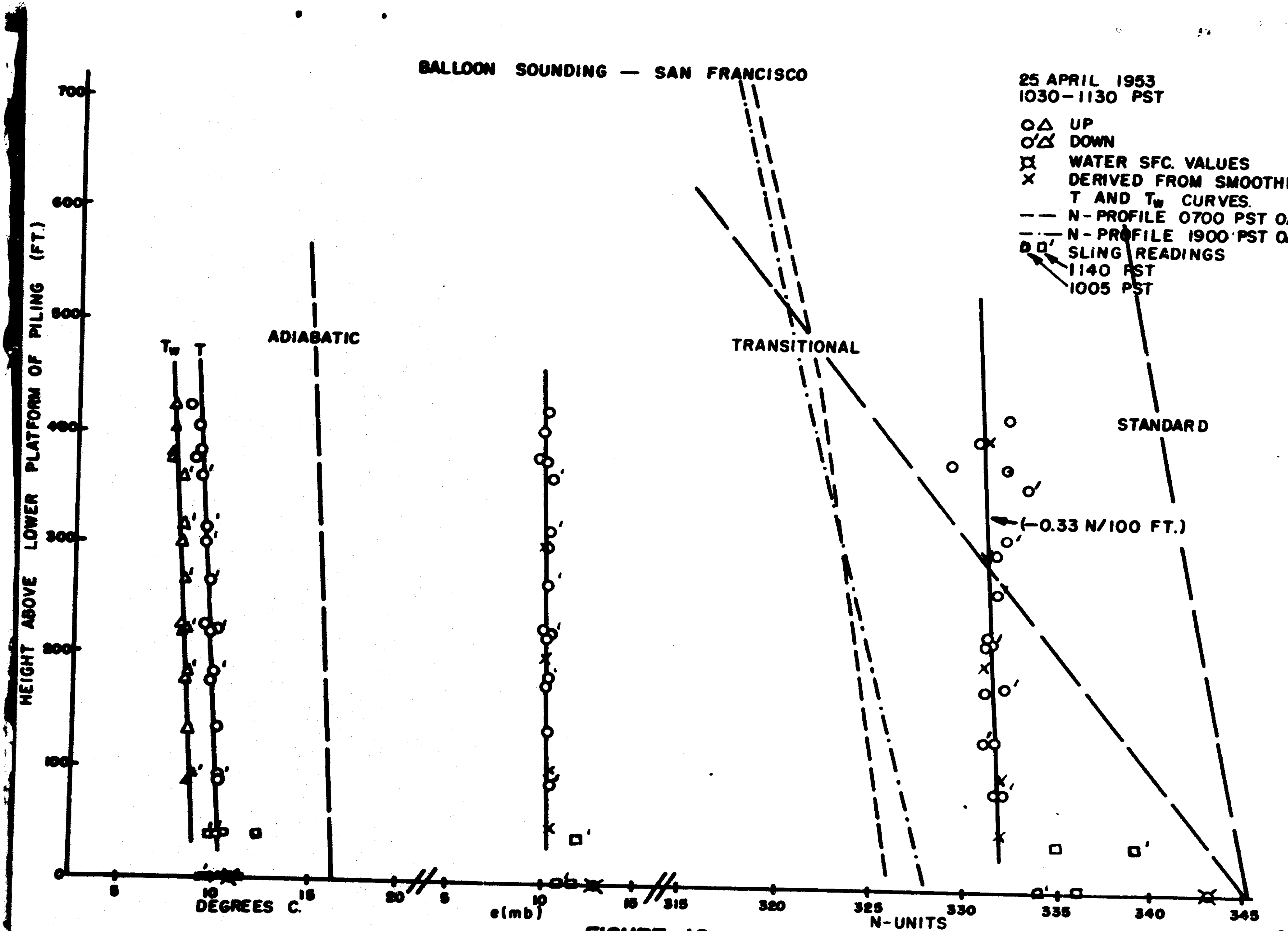


FIGURE 15


BALLOON SOUNDING — SAN FRANCISCO
25 APRIL 1953
1030-1130 PST
UP
DOWN
WATER SFC. VALUES
DERIVED FROM SMOOTHE
T AND T_w CURVES.
N-PROFILE 0700 PST O
N-PROFILE 1900 PST O
SLING READINGS
1140 PST
1005 PST
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT.)
T_w
T
ADIABATIC
TRANSITIONAL
STANDARD
(—0.33 N/100 FT.)
DEGREES C.
e(mb)
N-UNITS
0
100
200
300
400
500
600
700
5
10
15
20
5
10
15
315
320
325
330
335
340
345

N-UNITS

FIGURE 16

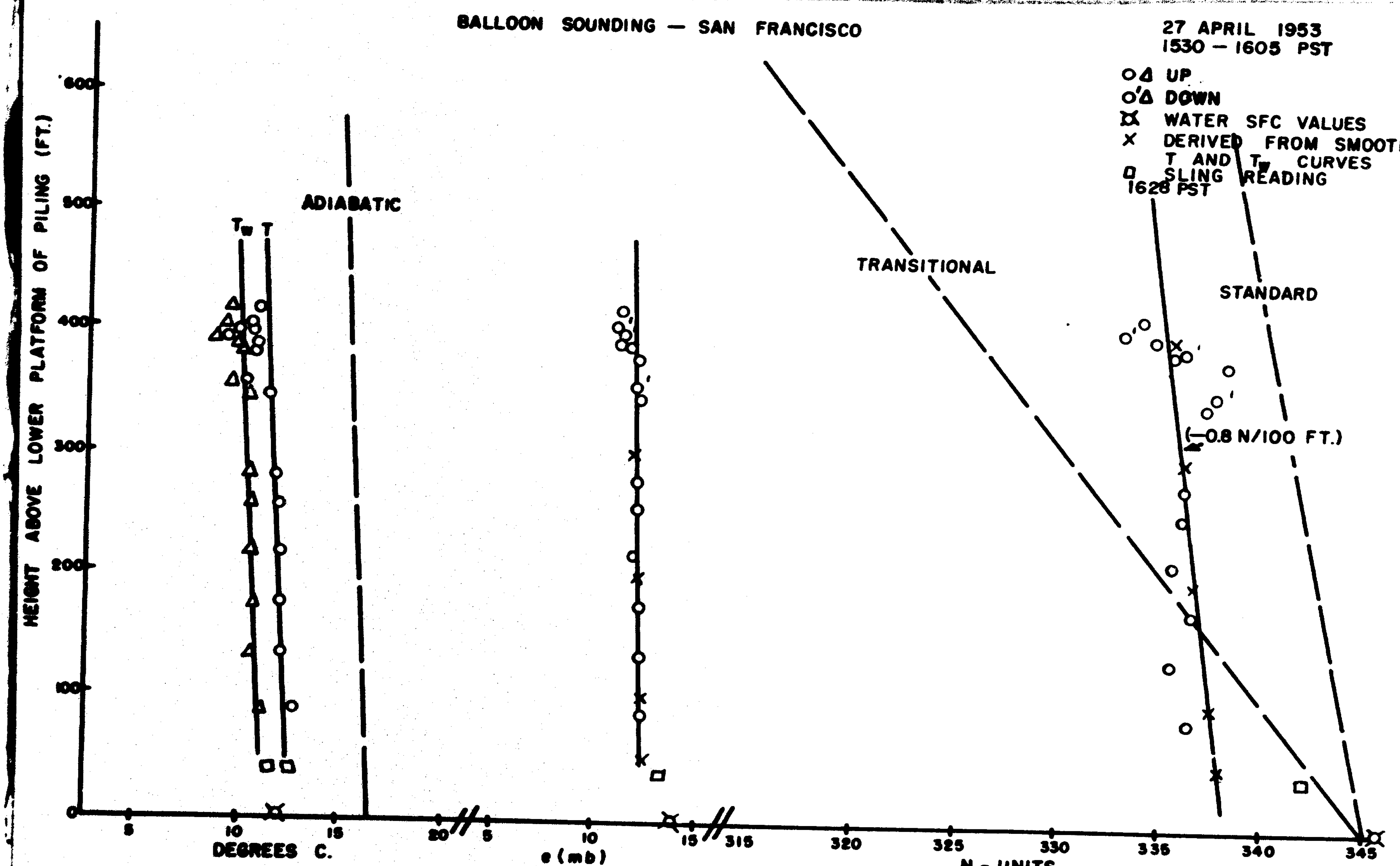


FIGURE 17

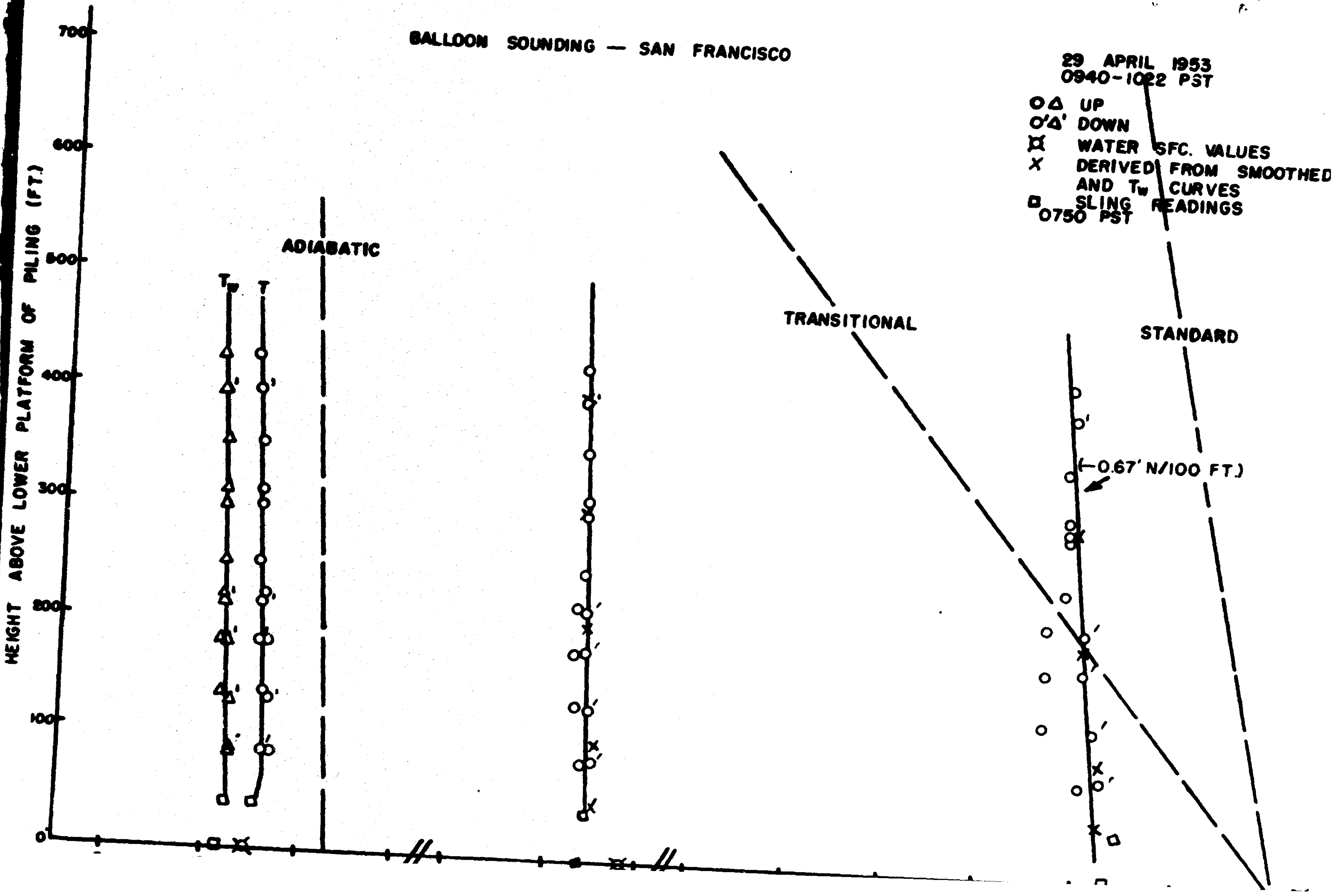

BALLOON SOUNDING — SAN FRANCISCO
29 APRIL 1953
0940-1022 PST
○ △ UP
○' △' DOWN
WATER SFC. VALUES
× DERIVED FROM SMOOTHED AND T_w CURVES
□ SLING READINGS 0750 PST
HEIGHT ABOVE LOWER PLATFORM OF PILING (FT.)
0
100
200
300
400
500
600
700
T_w
T
ADIABATIC
TRANSITIONAL
STANDARD
(−0.67' N/100 FT.)

TABLE 1

TABULATION OF METEOROLOGICAL SOUNDINGS

SAN FRANCISCO AREA, APRIL, 1953

SOUNDING NUMBER	DATE	TIME (PST)	TYPE
1.	31 Jan.	1505 - 1545	Balloon
2.	9 Feb.	1345 - 1440	Balloon
3.	2 Apr.	1430	Helicopter (N.G.?)(No EA records)
4.	3 Apr.	1030	Piling (No EA records)
5.	3 Apr.	1500	Helicopter (No EA records)
6.	7 Apr.	1000 - 1100	Balloon
7.	8 Apr.	1320 - 1500	Balloon
8.	9 Apr.	1000	Piling (No EA record)
9.	10 Apr.	1100 - 1200	Balloon
10.	13 Apr.	1000 - 1100	Balloon
11.	14 Apr.	1430 - 1545	Balloon
12.	17 Apr.	1400 - 1500	Balloon
13.	18 Apr.	1330 - 1500	Balloon
14.	20 Apr.	1100 - 1200	Balloon
15.	20 Apr.	1520 - 1620	Balloon
16.	21 Apr.	0950 - 1100	Piling (No EA record)
17.	21 Apr.	1600	Balloon (N.G.)
18.	23 Apr.	0920 - 1100	Balloon
19.	23 Apr.	1410 - 1500	Balloon
20.	24 Apr.	0920 - 1030	Balloon
21.	24 Apr.	1500 - 1558	Balloon
22.	25 Apr.	1030 - 1130	Balloon
23.	25 Apr.	1515 - 1640	Balloon
24.	27 Apr.	1530 - 1605	Balloon
25.	28 Apr.	1430 - 1530	Balloon (N.G.)
26.	29 Apr.	0940 - 1022	Balloon
27.	29 Apr.	1424 - 1520	Balloon

There were four instances in which relatively strong substandard gradients appeared to exist at heights from 250-400 feet above the normal essentially standard marine air mass refractive index profile. Some of these may well be instrumental since any wetting of the dry bulb sensing unit caused by excessive motion of the psychrograph would result in a fictitious decrease in the moisture lapse rate with a corresponding shift toward substandard gradients at that level. An example of this effect can be found in Figure 6 (8 April) where the strong substandard gradient beginning at about 350 feet corresponds to an increase in the temperature lapse rate to greater than adiabatic values. Since this condition is felt to be improbable, the lower level adiabatic lapse rate has been continued to the top of the sounding for April 8 (Figure 6) and April 23 (Figure 13) and the indicated superimposed substandard layers have been discounted. The two remaining cases illustrating this elevated substandard layer are found on April 13 (Figure 8) and April 17 (Figure 10). While such an effect cannot be corroborated by the available radiosonde data and no particular explanation can be offered, these soundings are certainly generally consistent with the others taken during this period and the elevated layers are believed to be real.

The single instance in which a well-marked duct occurred was on the afternoon of April 18 (Figure 11) when a pronounced sea breeze effect was observed in the refractive index profile at Baker Beach. Here, the marine air was penetrating landward in the lower levels, yielding an essentially standard profile up to 400 feet. Above this level, much drier air accounts for the super-refractive layer shown. It is not likely that the twin profiles above 400 feet represent significant differences in refractive index. However, the continued advection of marine air below this level apparently resulted in a substandard profile roughly an hour after the sounding began since the change from standard to substandard lapse rates in the lower 400 feet from ascent to descent readings is a significant one.

The afternoon of 18 April was particularly interesting meteorologically in that the sea breeze occurrence was aided and abetted by the advent of a rather sharp north-south high pressure ridge which moved in during the afternoon. The wind at the piling shifted at 1315 PST from northwest 7 miles per hour (mean) to west southwesterly 9 mph (mean), gusts to 15 mph. The average wind level did not change appreciably, but the sea breeze was definitely more gusty in character. By the time the sounding was made, one hour later, the marine air was about 400 feet deep over Baker Beach. The marine layer must have deepened significantly later in the day; at the 850 mb level, the dewpoint temperature changed from -8.5° C at 0700 PST to 2.5° C at 1900 PST. The air temperature was 8.2° C at both observations. The Oakland radiosonde observation reflects only the upper level moisture change. Again, the lower level phenomenon was localized.

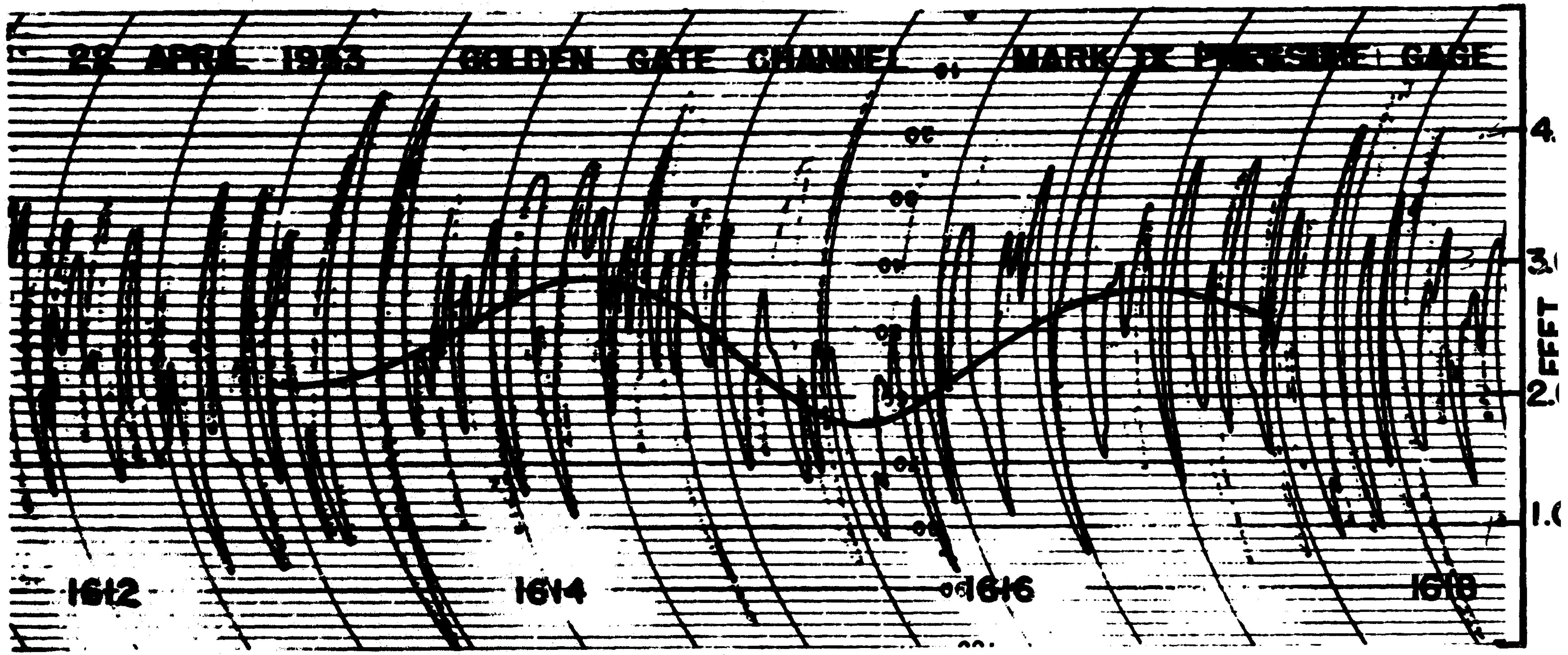
2. Synoptic Analysis. For the period of the tests, surface and 850 millibar charts of the western United States and the eastern Pacific Ocean were prepared from teletype data made available from the U. S. Weather Bureau station at San Francisco. The upper level charts were plotted and analyzed for 0700 and 1900 PST, and the surface map for 1030 PST. These maps were prepared for the purpose of determining weather patterns on a large scale as related to the observed

occurrences of wind, waves, and atmospheric characteristics in the Golden Gate area. For the most part, however, as mentioned previously, the scale of operations at Baker Beach was such that with the exception of the normal standard refractive index gradient, little correlation could be found between the local occurrences and the broad scale weather features. An exception to this has already been noted for the afternoon of 18 April. It appears, therefore, that meteorological analyses of the kind reported for the Point Mugu area [4] are not possible in the present case, partly because of the unavailability of overwater refractive index profiles to higher levels, and partly because of path length and location as related to broad scale weather patterns. It should be mentioned parenthetically that the same problem of scale prevented an adequate analysis of ocean surface characteristics as related quantitatively to meteorological parameters such as wind. As a substitute, a few scatter diagrams were prepared of observed wave heights at the piling as a function of wind speed not only at the piling, but from weather maps (averages for the San Francisco area) and from 850 millibar chart as a more reliable indicator of flow patterns. The results of this study were entirely negative.

B. Oceanographic Findings.

1. General Oceanography. Although the Golden Gate radio path had many of the desired geometrical characteristics for a careful study of the reflection of microwave radio energy from water surfaces of varying degrees of roughness, the channel itself has a rather complex associated oceanography. Currents in the channel were quite strong and standing wave patterns formed by the interaction of the outflow and inflow currents appeared as the rule rather than as the exception. Significant horizontal variations in the wave structure could often be observed visually over the entire outer portion of the channel. The deep basin nature of the channel also appeared on occasion to be responsible for the appearance of surge type water surface variations similar to those reported on coastal installations by Munk [5] and Yoshida [11] and which would not be representative of open water conditions. Thus, on April 22 for instance, waves having periods of 2½ to 3 minutes and amplitudes of up to 1 foot were noted in both the pressure and step gage recordings. These particular wave patterns showed up very distinctly on the relatively large amplitude slow speed pressure gage recordings but were very difficult to determine on the higher speed lower amplitude recordings used for the simultaneous step, pressure and continuous-wire recordings. Although a thorough examination of the data has not been made, significant surge effects were noticeable only on the 22nd with some indications present on the 23rd and 24th. However, whether this represents some natural vibration frequency of the channel, or as suggested by Yoshida, represents a frequency present (but of possibly too low an amplitude to be detectable) in all wave patterns near shore locations, cannot be determined. An example of this wave pattern is shown in Figure 18a.

In an effort to obtain qualitative indications of the extent to which horizontal homogeneity existed in the wave pattern over the channel, a series of water surface photographs were taken of the channel to include the radiopaths



PRESSURE GAGE RECORDING SHOWING SURGES IN GOLDEN GATE CHANNEL

FIGURE 18 a

and the piling. These pictures, however, were taken infrequently and the lack of detail made them difficult to interpret. Thus, with the possible exception of being able to determine the directional orientation of major swells, it has not been possible to make horizontal homogeneity evaluations for the normal 5-20 minute data gathering period.

2. Wave Analysis. The analysis of the wave gage data has proceeded along two major lines. The first, which may be termed a statistical approach, is still underway and will be reported separately. In the statistical analysis, extensive use is being made of the correlation computer developed at this Laboratory, and the results are largely in terms of auto-correlations, probability distributions and power spectra.

The second approach has been what might be termed a synoptic one, with emphasis on the broad scale features of the wave patterns. This analysis has been semi-statistical, and has used limited portions of the data to characterise such parameters as wave period, wave heights, and wave height ratios for the entire period of observations. In addition, a comparison of the records obtained from the three wave gages has been made and the results are reported.

A complete catalog of all wave data taken during the test period is found in Table 2.

The output of the University of California pressure gage was recorded nearly continuously on a motor-driven Esterline-Angus 0-1 m.a. recorder at a paper speed of 1½" per minute. The data have been analyzed according to the method outlined by Snodgrass and Stiling [9]. Representative 20-minute periods were selected for mornings and afternoons by visual inspection of the original records, for the period 6-27 April 1953. From these sets of data were found: (a) characteristic wave period, T, in seconds (defined as the average period for the well-defined series of highest waves observed during the 20-minute period); (b) characteristic wave height, $H_{1/3}$, in feet (defined as the average height of 33 1/3 per cent of the highest waves); (c) maximum wave height, H_{max}, in feet (highest wave recorded in the 20-minute interval); and (d) the ratio of H_{max} to $H_{1/3}$. The results of this analysis appear in Figure 19 with the actual data given in Table 3.

In addition, in part to check the apparent representivity of these points and to check the time trends of these parameters, a second set of 20-minute periods of data were chosen from the E.-A. trace. Here, an effort was made to select data for a time for which no analysis had been made rather than for the most representative data during a morning or an afternoon. These points are also plotted on Figure 19. There are no systematic differences between these two sets, suggesting that the time-trends of wave periods and wave heights are not distorted materially by the choice of analysis periods.

It is seen that the characteristic wave period decreases uniformly from 10 seconds to about 7 seconds over the period from 6-13 April, then increases

TABLE 2

TABULATION OF WAVE DATA

SAN FRANCISCO AREA, APRIL, 1953

DATE	TIME (PST)	TYPE
16 February	1324-1433	P
	1321-1345	CA, S
17 February	1318-1336; 1535-1550	P
	1312-1320; 1523-1528; miscellaneous	CA, S
18 February	1125-1156; 1340-1404; 1555-1630	P
	1140-1151; miscellaneous	CA, S, P
19 February	0925-0942; 1003-1024; 1141-1331	
	1347-1650	P
	0929-0939; 1003-1024; miscellaneous	CA, S, P
20 February	0853-1305; 1335-1435; 1439-1630	P
	0847-0858; miscellaneous	CA, S, P
4 April	1029-1042; 1350-1401; 1544-1605	CA, CS, S
6 April	0906-0918; 1030-1103; 1123-1137	
	1145-1159; 1341-1355; 1409-1420	
	1430-1442; 1450-1500; 1512-1518	
	1530-1542; 1623-1651; 1728-1744	CA, CS, S
	0904-0920; 1030-1116; 1123-1137	
	1144-1159; 1341-1355; 1407-1420	
	1428-1443; 1447-1501; 1507-1520	
	1529-1542; 1623-1650; 1728-1743	P
7 April	1101-1112; 1246-1302; 1332-1348	
	1418-1434; 1510-1525; 1548-1604	CA, CS, S
	1245-1302; 1331-1348; 1417-1434	
	1509-1525; 1546-1602	P
8 April	1051-1105; 1356-1410; 1420-1433	
	1505-1521; 1544-1634	CA, CS, S
	1357-1432; 1504-1521; 1544-1632	P
9 April	1041-1056; 1132-1146; 1331-1346	
	1434-1450; 1503-1516; 1530-1549	CA, CS, S
	1332-1346; 1434-1451; 1503-1516	
	1530-1546; 1609-1620	P
10 April	0923-0941; 1029-1046; 1100-1116	
	1139-1154; 1228-1244; 1306-1324	
	1348-1406; 1430-1446; 1512-1526	
	1600-1610	CA, CS, S
	0740-0806; 0923-0939; 1029-1046	
	1100-1116; 1138-1216; 1228-1244	
	1306-1357; 1410-1416; 1430-1446	
	1508-1529	P
11 April	0904-0924; 1020-1036; 1124-1140	
	1340-1356	CA, CS, S
	0904-0927; 1018-1036; 1124-1140	
	1310-1359	P

TABLE 2 (Continued)

DATE	TIME (PST)	TYPE
13 April	1326-1340; 1445-1500; 1525-1540	
	1616-1632	CA, CS, S
	1325-1359; 1446-1510; 1525-1540	P
14 April	1358-1414; 1446-1500; 1540-1555	
	1606-1622	CA, CS, S
	1009-1025; 1359-1414; 1447-1500	
	1543-1555; 1605-1622	P
15 April	0956-1009; 1125-1140; 1300-1315	
	1330-1345, 1402-1416; 1441-1458	
	1522-1538; 1605-1621	CA, CS, S
	0926-0940; 1124-1140; 1300-1315	
	1329-1345; 1402-1416; 1523-1538	
	1606-1621	P
16 April	1137-1146; 1402-1419; 1452-1508	
	1556-1611	CA, CS, S
	1137-1203; 1404-1420; 1446-1511	
	1556-1611	P
17 April	1336-1617	P
18 April	1011-1551	P
20 April	1034-1053; 1351-1408; 1459-1515	
	1552-1607; 1620-1634; 1646-1658	S
	1002-1702	P
21 April	1114-1128; 1145-1152; 1318-1334	
	1350-1402; 1416-1431; 1446-1500	
	1530-1547; 1552-1606; 1622-1635	S
	1124-1645	P
22 April	0930-0946; 1022-1037; 1110-1125	
	1149-1204; 1334-1350; 1413-1428	
	1448-1504; 1525-1540; 1602-1617	
	1003-1018; 1051-1106; 1130-1145	
	1354-1410; 1430-1445; 1506-1522	
	1543-1558; 1620-1640	S
	0834-1632	P
23 April	0956-1012; 1035-1050; 1114-1129	
	1315-1330; 1352-1415; 1451-1507	
	1536-1552; 1613-1630	
	0937-0952; 1016-1032; 1055-1110	
	1137-1155; 1333-1348; 1432-1448	
	1518-1533; 1554-1610; 1633-1648	S
	0806-1653	P
24 April	0936-0957; 1025-1040; 1101-1117	
	1147-1202; 1347-1403; 1436-1452	
	1523-1539: 1614-1630	
	1007-1023; 1042-1058; 1127-1143	
	1327-1342; 1407-1422; 1500-1518	
	1549-1605; 1633-1648; 1657-1725	S
	0800-1728	P

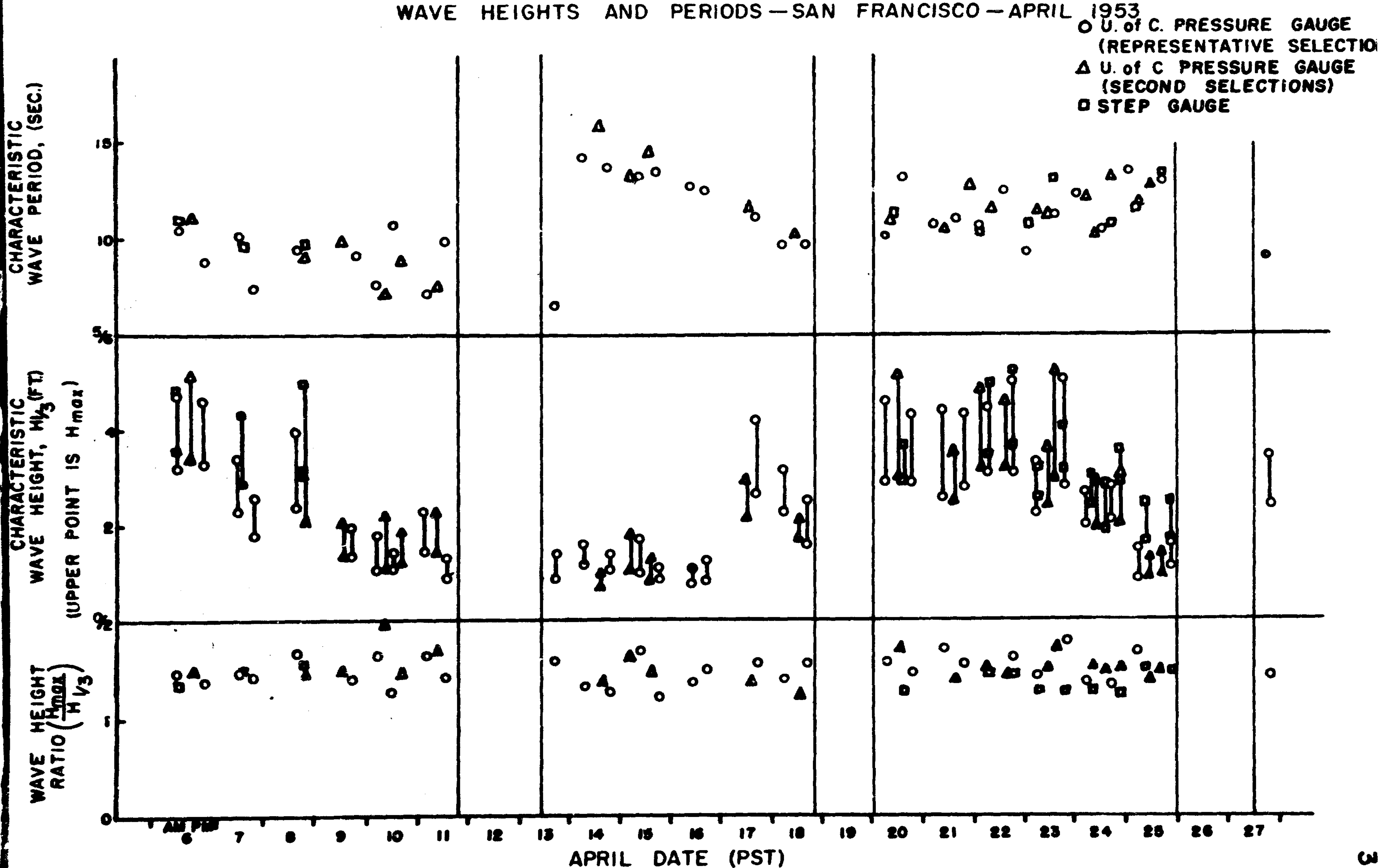
TABLE 2 (Continued)

DATE	TIME (PST)	TYPE
25 April	1005-1020; 1041-1056; 1119-1134	
	1334-1349; 1415-1430; 1519-1534	
	0947-1002; 1023-1038; 1100-1115	
	1137-1152; 1315-1330; 1352-1410	
	1446-1503; 1537-1553; 1558-1614	
	1617-1643; 1650-1720; 1723-1757	S
	0819-1800	P
27 April	1454-1506; 1513-1523; 1528-1545	
	1558-1606; 1610-1623	S
	1433-1625	P
28 April	1010-1027; 1230-1245; 1302-1314	
	1346-1359; 1431-1442; 1502-1514	
	1531-1544	
28 April*	0931-0947; 1042-1101; 1247-1259	
	1317-1329; 1402-1415; 1445-1459	
	1516-1529; 1549-1615; 1636-1651	
	1654-1712; 1725-1740; 1743-1758	
	1803-1830; 1851-1909	S
29 April	0814-0829; 0835-0856; 0918-0931	
	1019-1026; 1032-1045; 1056-1112	
	1138-1156; 1209-1227; 1231-1246	
	1322-1338; 1346-1401; 1407-1421	
	1425-1440; 1507-1522; 1543-1555	
	1611-1626; 1643-1700; 1704-1720	
	1724-1740; 1802-1817; 1820-1835	
	1838-1854; 1858-1911	S

* Some short synchronized step gage and movie data taken between 0914-0920.

CODE:

CA Continuous-wire Gage Amplitude
CS Continuous-wire Gage Slopes
S Step Gage Amplitude
P Pressure Gage Amplitude



WAVE HEIGHTS AND PERIODS — SAN FRANCISCO — APRIL 1953
O U. of C. PRESSURE GAUGE (REPRESENTATIVE SELECTIO
Δ U. of C PRESSURE GAUGE (SECOND SELECTIONS)
□ STEP GAUGE
CHARACTERISTIC WAVE PERIOD, (SEC.)
CHARACTERISTIC WAVE HEIGHT, $H_{1/3}$ (FT)
(UPPER POINT IS H_{max})
WAVE HEIGHT RATIO $\left(\frac{H_{max}}{H_{1/3}}\right)$
15
10
5/6
4
2
0/2
1
0
AM PM
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
APRIL DATE (PST)

FIGURE 19

TABLE 3

WAVE ANALYSES

UNIVERSITY OF CALIFORNIA PRESSURE GAGE

APRIL, 1953

Date	Time	Period (Sec)	$H_{1/3}$ (Ft)	H_{max} (Ft)	$H_{max} / H_{1/3}$
April 6	1040-1100	10.4	3.2	4.7	1.47
	1100-1116	10.45	3.0	4.3	1.43
	1122-1137		3.4		
	1143-1159		3.0		
	*1340-1355	11.0	3.4	5.1	1.50
	1407-1420		3.35		
	1428-1443		3.1		
	1448-1501		3.8		
	1507-1520		3.7		
	1529-1542		3.9		
	1626-1646	8.75	3.3	4.6	1.39
	1728-1743		2.9		
April 7	1245-1302	10.0	2.3	3.4	1.48
	1331-1348		2.3		
	1417-1434		2.2		
	1509-1525		2.0		
	1546-1602	7.3	1.8	2.6	1.44
April 8	1357-1412		2.4		
	1412-1432	9.35	2.4	4.0	1.67
	1504-1521		2.6		
	1543-1603		2.4		
	*1610-1630	9.0	2.1	3.1	1.48
April 9	*1331-1346	9.7	1.4	2.1	1.50
	1530-1546	9.0	1.4	2.0	1.43
April 10	0923-0939	7.5	1.1	1.8	1.64
	*1100-1116	7.0	1.1	2.2	2.00
	1306-1324	10.6	1.1	1.4	1.27
	*1509-1529	8.8	1.3	1.9	1.46
April 11	0902-0922	7.0	1.4	2.3	1.64
	*1123-1140	7.4	1.4	2.3	1.64
	1315-1335	9.7	0.91	1.3	1.43
April 13	1525-1540	6.5	0.88	1.4	1.59
April 14	1009-1025	14.1	1.2	1.6	1.33
	*1358-1414	15.8	0.74	1.0	1.35
	1605-1622	13.6	1.1	1.4	1.27
April 15	*0925-0940	13.1	1.1	1.8	1.64

*Second Selections

Date	Time	Period (Sec)	$H_{1/3}$ (Ft)	H_{max} (Ft)	$H_{max}/H_{1/3}$
April 15	1124-1140	13.1	1.0	1.7	1.70
	*1329-1345	14.4	0.88	1.3	1.48
	1522-1538	13.3	0.90	1.1	1.22
April 16	1141-1201	12.6	0.81	1.1	1.36
	1451-1511	12.3	0.87	1.3	1.49
April 17	*1335-1355	11.5	2.2	3.0	1.36
	1533-1553	11.0	2.7	4.2	1.56
April 18	1020-1040	9.5	2.3	3.2	1.39
	*1240-1300	9.9	1.7	2.1	1.23
	1455-1515	9.5	1.6	2.5	1.56
April 20	1007-1027	9.9	2.9	4.6	1.58
	*1250-1310	10.8	3.0	5.1	1.70
	1540-1600	13.0	2.9	4.3	1.48
April 21	1125-1145	10.5	2.6	4.4	1.69
	*1400-1420	10.2	2.5	3.5	1.40
	1625-1645	10.8	2.8	4.3	1.54
April 22	*0834-0854	12.5	3.2	4.8	1.50
	1000-1020	10.5	3.1	4.4	1.42
	*1300-1320	11.3	3.2	4.6	1.73
	1544-1604	12.3	3.1	5.0	1.61
April 23	0930-0950	9.1	2.3	3.3	1.43
	*1140-1200	11.1	2.4	3.6	1.50
	*1400-1420	11.0	3.0	5.2	1.73
	1619-1639	11.0	2.8	5.0	1.79
April 24	0915-0935	12.1	2.0	2.7	1.35
	*1110-1130	11.9	2.0	3.0	1.50
	*1315-1335	10.0	1.9	2.8	1.47
	1520-1540	10.3	2.1	2.8	1.33
	*1708-1728	10.4	2.0	3.0	1.50
April 25	0920-0940	13.3	0.89	1.5	1.68
	*1140-1200	11.7	0.94	1.3	1.38
	*1430-1450	12.6	0.95	1.4	1.47
	1727-1747	12.8	1.1	1.6	1.45
April 27	1515-1535	9.1	2.4	3.4	1.42

*Second Selections

sharply to near 15 seconds less than 24 hours later. The only explanation found for this phenomenon is in the character of the wave records for the two periods (afternoon of the 13th and morning of the 14th). Over the time interval from the 6th to the 13th of April, both wave heights and periods declined, until the wave record took on the appearance shown in the top half of Figure 20. Groups of significantly high waves are difficult to discern, and the overall pattern is one of numerous waves of relatively small amplitude, and with a reasonably uniform wavelength or wave speed or both. On the morning of the 14th, however, groups of significant waves again appeared; these waves were longer or slower, or both, than those of the 13th, with the result that the computed characteristic wave period more than doubled, although wave heights showed no material change. To what extent this increase in period is peculiar to the inlet itself and whether it is representative of conditions over the entire Golden Gate area, however, cannot be determined from the data at hand. True, the light ship off the Golden Gate reported no such change and periods of waves passing the light ship were always in the order of 5 or 6 seconds, with no significant change reported during the entire period from 6 to 27 April. However, the lower and constant wave period from the light ship may well be as much a result of the consequence of counting all waves rather than only groups of significant waves, as it is a consequence of the open water location of the light ship.

Finally, the H_{max} to $H_{1/3}$ wave height ratios in Figure 19 are seen to average near 1.5 for the entire period of record, with overall variations from 1.2 to 2.0. This finding is at considerable variance with identical ratios reported in the literature from different locations. These reported values average near 1.85 [10], an increase of about 20% over 1.5. The suggestion is strong here that the records from the Golden Gate location cannot be compared with those obtained from more exposed coastal locations like Point Arguello and Cuttyhunk. The relatively short record of one month obtained during the test period must also be kept in mind.

The step wave gage output was placed on an Edin recorder, which was run at varying speeds, depending on the type of record being obtained. Most of the records were at 2.5 mm per second. The same (Snodgrass) method of analysis was applied to a limited number of these records, and the results again plotted on Figure 19. The actual data are given in Table 4a. It will be noted that in general the step gage findings agree with those of the pressure gage, with an important exception in the characteristic ($H_{1/3}$) wave heights. It will be noticed from Table 4b, which gives the comparable $H_{1/3}$ values for step and pressure gage recordings, that with one exception the actual wave heights measured with the step gage exceed those computed from the pressure gage record. Although the times are not always synchronous and there are only a few data available for comparison, the average pressure gage wave heights are certainly of the order of 25% too low. Whether or not the extremely high ratio indicated for April 25 is real cannot be determined but there may be an indication in this data that the amplitude discrepancy might be an inverse function of wave amplitude. This comparison between step and pressure gage records will be explored further in a later section.

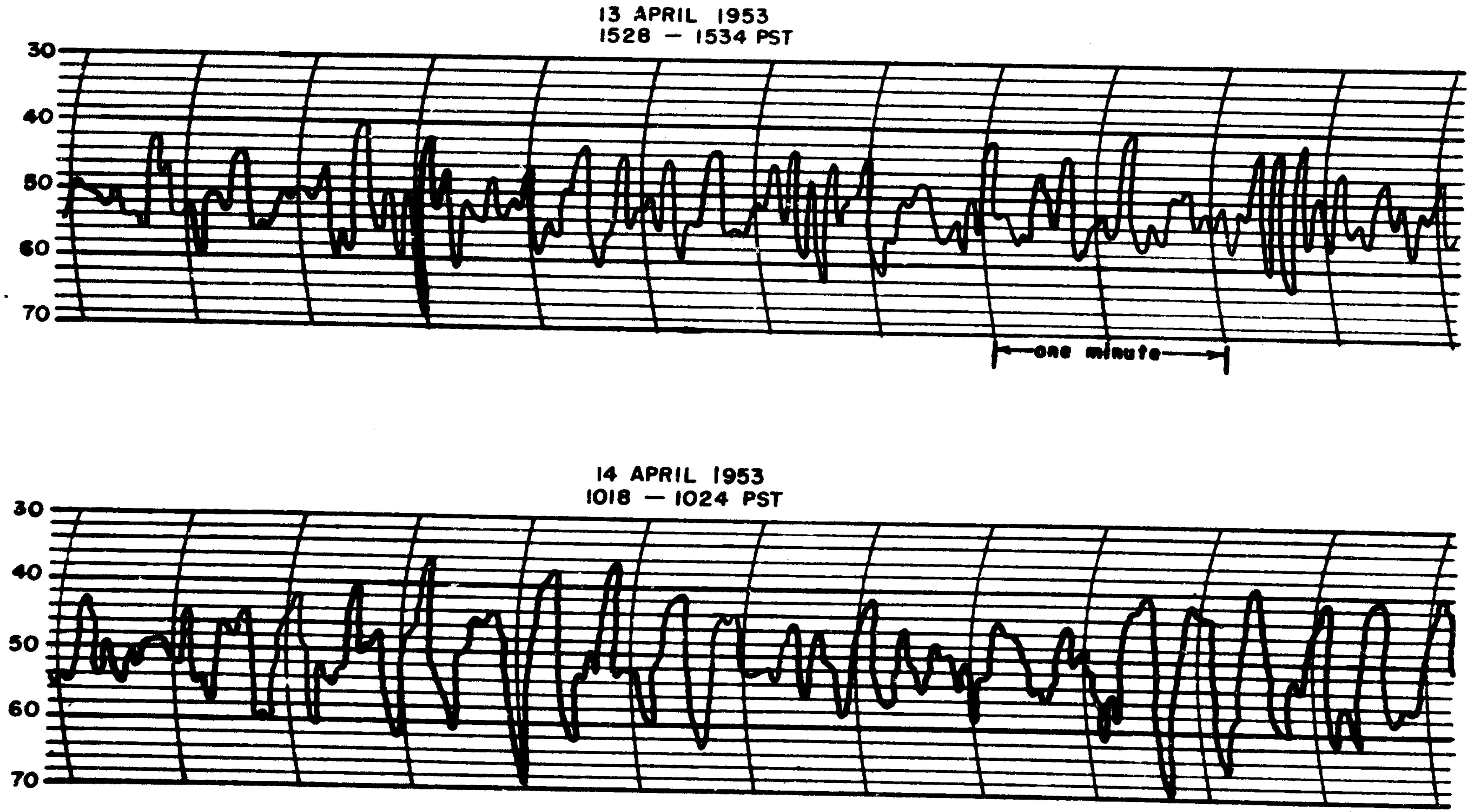


FIGURE 20

PRESSURE GAUGE WAVE RECORDS SHOWING CHANGE IN WAVE PATTERNS
13-14 APRIL 1953 (TRACED FROM ORIGINAL)

TABLE 4a

STEP GAGE WAVE ANALYSES BY SNODGRASS METHOD

Date	Time	Period (Sec)	$H_{1/3}$ (Ft)	H_{max} (Ft)	$H_{max} / H_{1/3}$
April 6	1041-1101	11.0	3.55	4.80	1.35
April 7	1331-1348	9.5	2.89	4.30	1.49
April 8	1600-1620	9.7	3.17	4.89	1.54
April 20	1351-1408	11.1	2.90	3.66	1.26
April 22	1003-1018	10.0	3.45	4.98	1.44
	1543-1558	12.1	3.60	5.20	1.44
April 23	1016-1032	10.5	2.55	3.18	1.25
	1554-1610	12.8	3.20	4.04	1.26
April 24	1042-1058	12.1	2.41	3.06	1.27
	1705-1725	10.5	2.90	3.54	1.22
April 25	1100-1115	11.3	1.65	2.44	1.48
	1727-1747	13.2	1.71	2.44	1.43

TABLE 4b

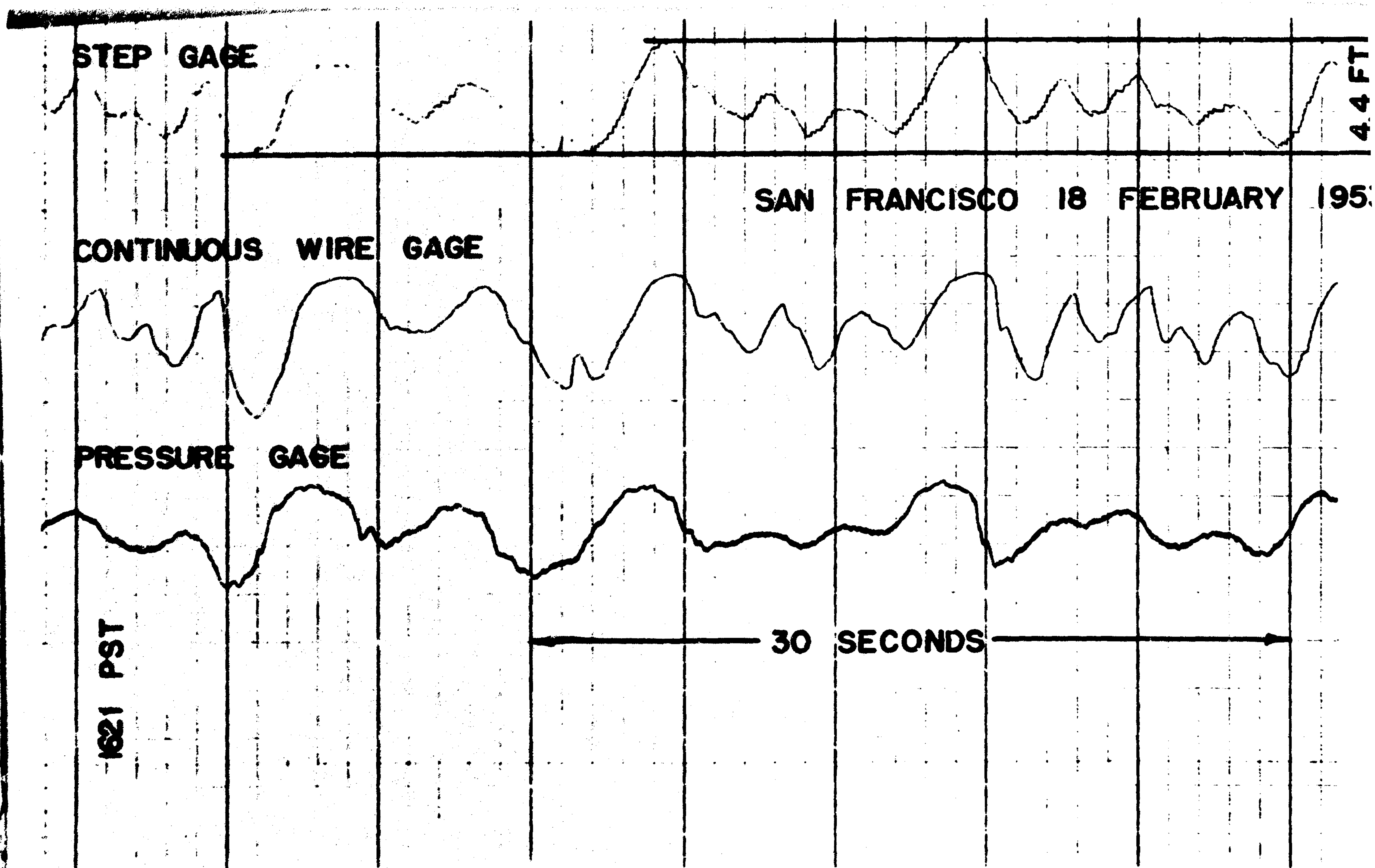
COMPARISON OF SNODGRASS METHOD OF $H_{1/3}$ EVALUATION

FOR PRESSURE AND STEP GAGE DATA

Date	Time Pressure Gage	Time Step Gage	$H_{1/3}$ Pressure Gage	$H_{1/3}$ Step Gage	$H_{1/3}$ Ratio Step/Pressure
April 6	1040-1100	1041-1101	3.2	3.55	1.11
April 7	1331-1348	1331-1348	2.3	2.89	1.26
April 8	1610-1630	1600-1620	2.1	3.17	1.51
April 20	1250-1310	1351-1408	3.0	2.90	0.97
April 22	1000-1020	1003-1018	3.1	3.45	1.11
	1544-1604	1543-1558	3.2	3.60	1.12
April 23	0930-0950	1016-1032	2.3	2.55	1.11
	1619-1639	1554-1610	2.8	3.20	1.14
April 24	1110-1130	1042-1058	2.0	2.41	1.20
	1708-1728	1705-1725	2.0	2.90	1.45
April 25	1140-1200	1100-1115	0.94	1.65	1.76
	1727-1747	1727-1747	1.1	1.71	1.55
				Average	1.27

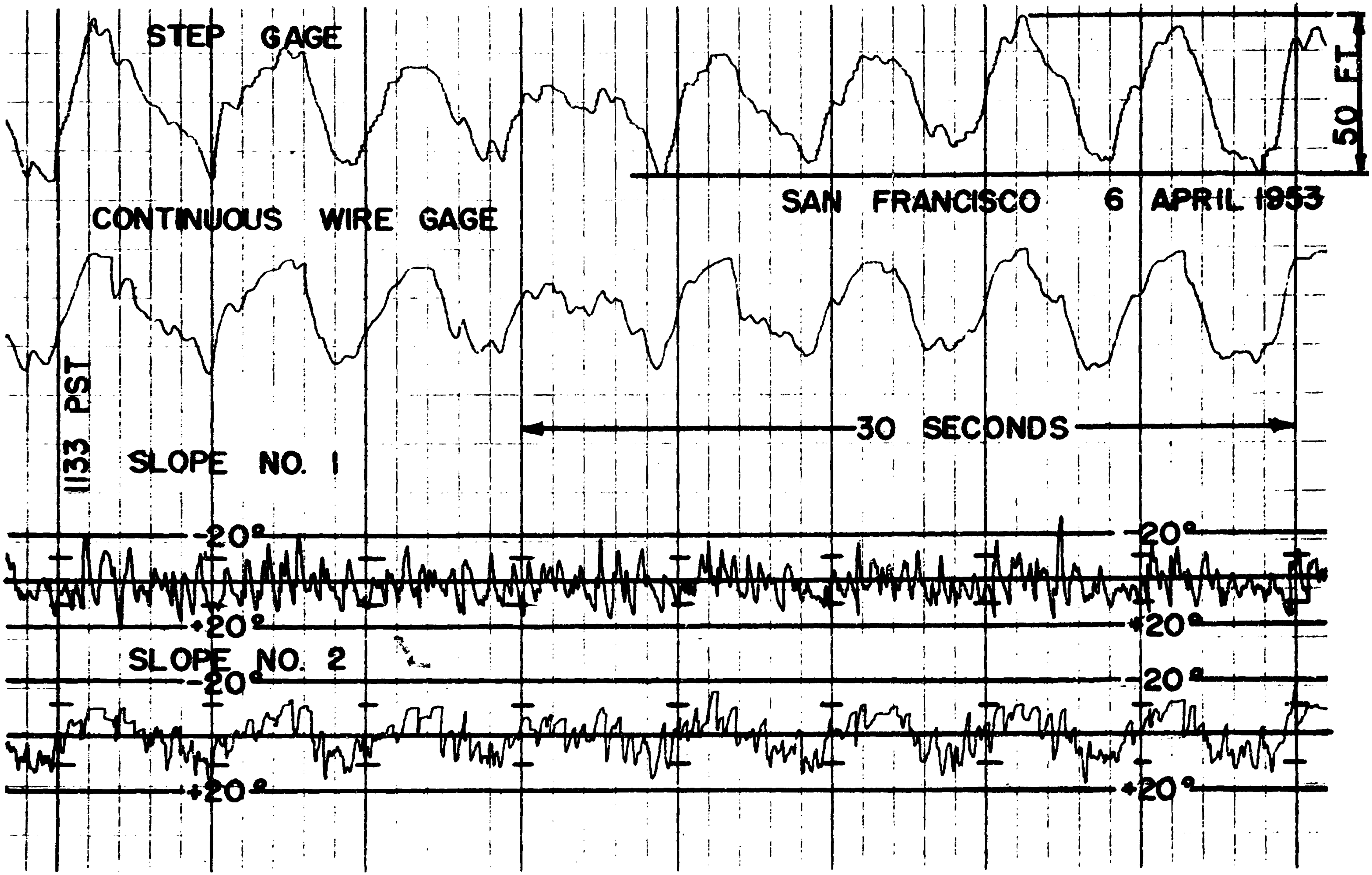
The continuous-wire gage, designed to give a continuous rather than a discrete record of waves for statistical analysis purposes, had its output placed on a second channel of the Edin recorder, making a simultaneous record with the step gage. There was an obvious one-to-one correlation of the two records, such that the need for a detailed analysis of the continuous-wire records was obviated. As a matter of fact, the step gage was intended to supply the calibration for the continuous-wire gage. The essentially identical patterns of the step and continuous wire gages and the marked loss of sensitivity for the pressure gage can be seen very easily in Figure 20a, which shows a representative and simultaneous set of recordings of the outputs of all three gages. It can be noted that waves having periods of 1-2 seconds are completely missing from the pressure gage record and waves with periods up to 3-4 seconds have a considerably reduced amplitude. Note in the step gage output that clearly defined steps can be seen only during periods when the water surface is rising. The finite time of water runoff from the gage (during falling water periods) smooths the step gage record. The apparent phase differences between the three recordings is not real. Different lengths of recording pens were inadvertently used in the initial observation periods and an artificial phase lead was generated in the Edin recording of the pressure gage output.

Further details of the comparison between step and continuous-wire recordings with particular emphasis on the record obtained from the wave slope units of the continuous-wire gage are shown in Figures 21 through 24. Visual inspection of these simultaneous amplitude and slope wave records show some very interesting features and although no significant analysis of the slope data has been made, one can, in a sense, reconstruct the characteristics of the water surface at the piling by the comparison of the two records. The data for April 6, for instance, shown in Figure 21, contain some of the highest amplitude waves noted during the entire observation period and there is a marked difference between the two slope recordings in contrast to their more normal essentially similar patterns. The obvious correspondence of the same fundamental swell period in both the amplitude and slope 2 records would indicate that the high amplitude waves are sufficiently steep so that a slope measuring device operating over a distance of six inches is sufficient to describe both the major wave profile and the superimposed smaller water surface variations. The lack of this major period in the slope 1 record would appear to indicate that the wave crests are traveling essentially parallel to the slope 2 direction, i.e., from the northwest. Two other features of the slope records might be worth pointing out. The frequencies in the slope variations are, as is to be expected, much higher than those for the amplitude variations. These changes, however, can on occasion be so rapid as to give essentially vertical lines on the recordings. Since the amplitude traces never show such high frequency effects, they must be due to some combination of rapidly moving, forming or dissipating very short wavelength water surface perturbations-of the order of 6 inches-superimposed on the ordinary sea structure. A few such instances can be noted in the slope recordings shown in Figure 21. Finally, we can see in the slope 2 recording of the same figure some very unusual flattened traces. Since there is no reason to suspect instrument malfunctioning, sections of the profiles of relatively large waves appear to have essentially constant slopes.



SIMULTANEOUS RECORDING OF STEP, CONTINUOUS WIRE, AND PRESSURE GAGES

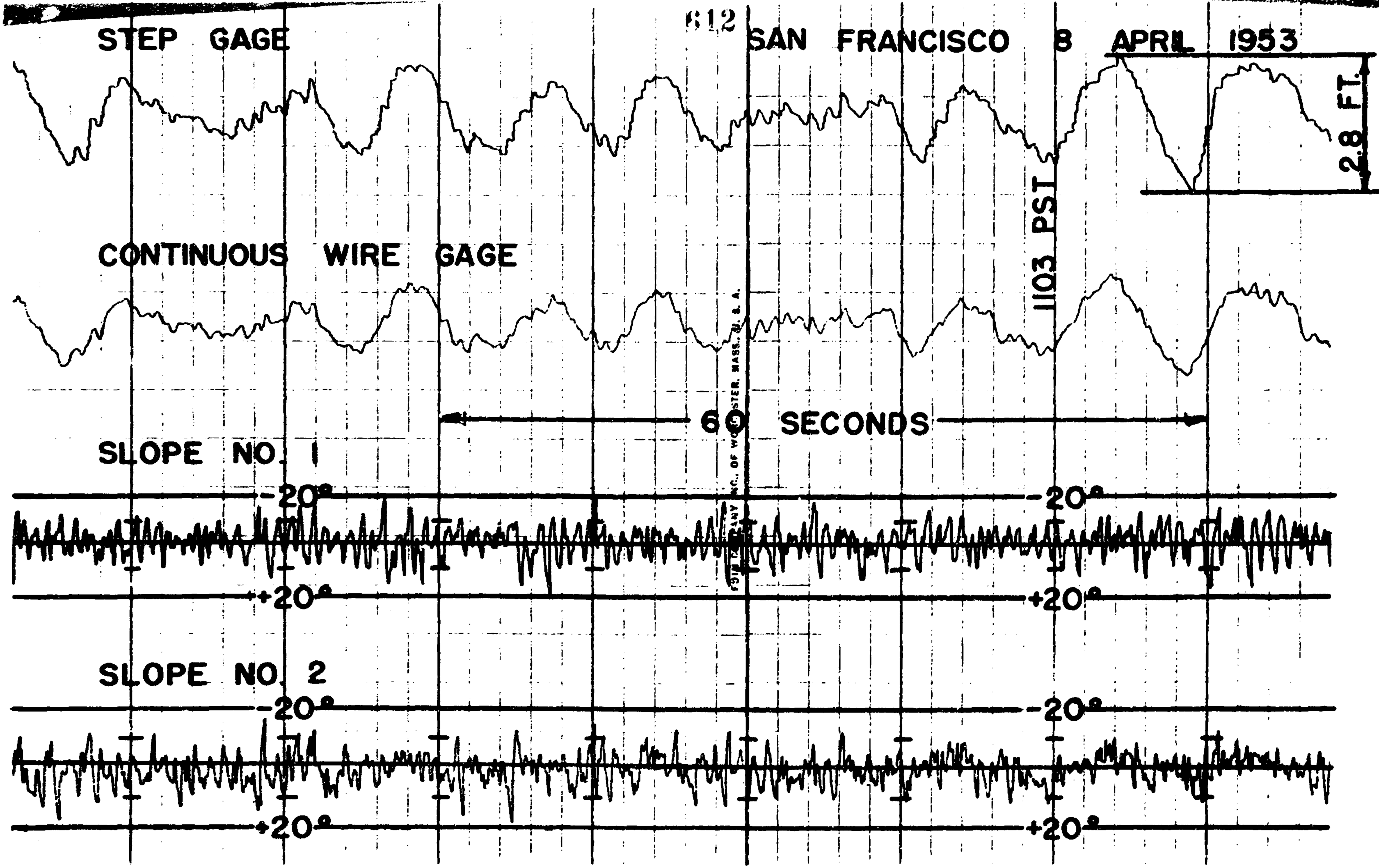
FIGURE 20 a



SIMULTANEOUS RECORDING OF STEP AND CONTINUOUS WIRE GAGES

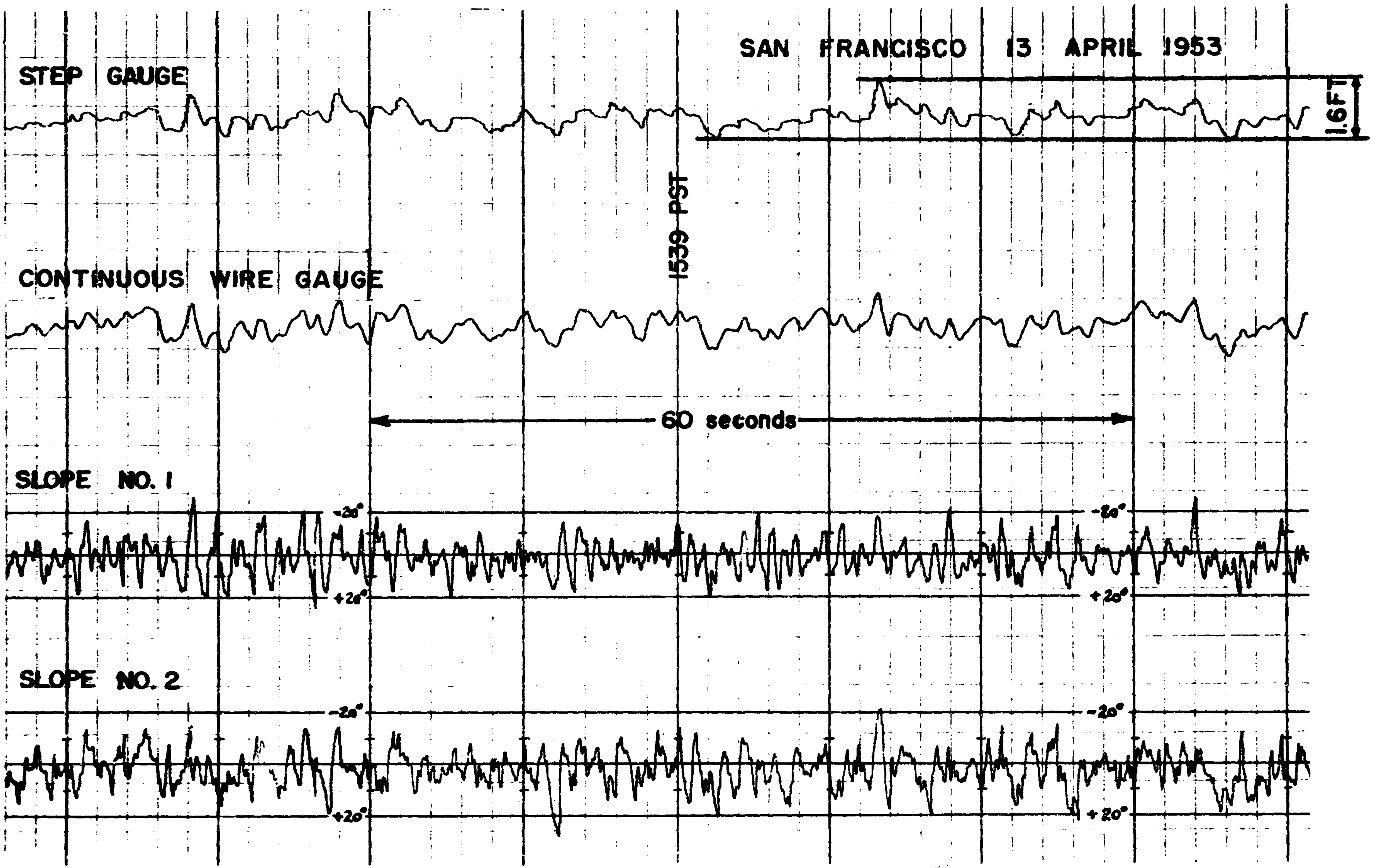
FIGURE 21

FIGURE 21



SIMULTANEOUS RECORDING OF STEP AND CONTINUOUS WIRE GAGES

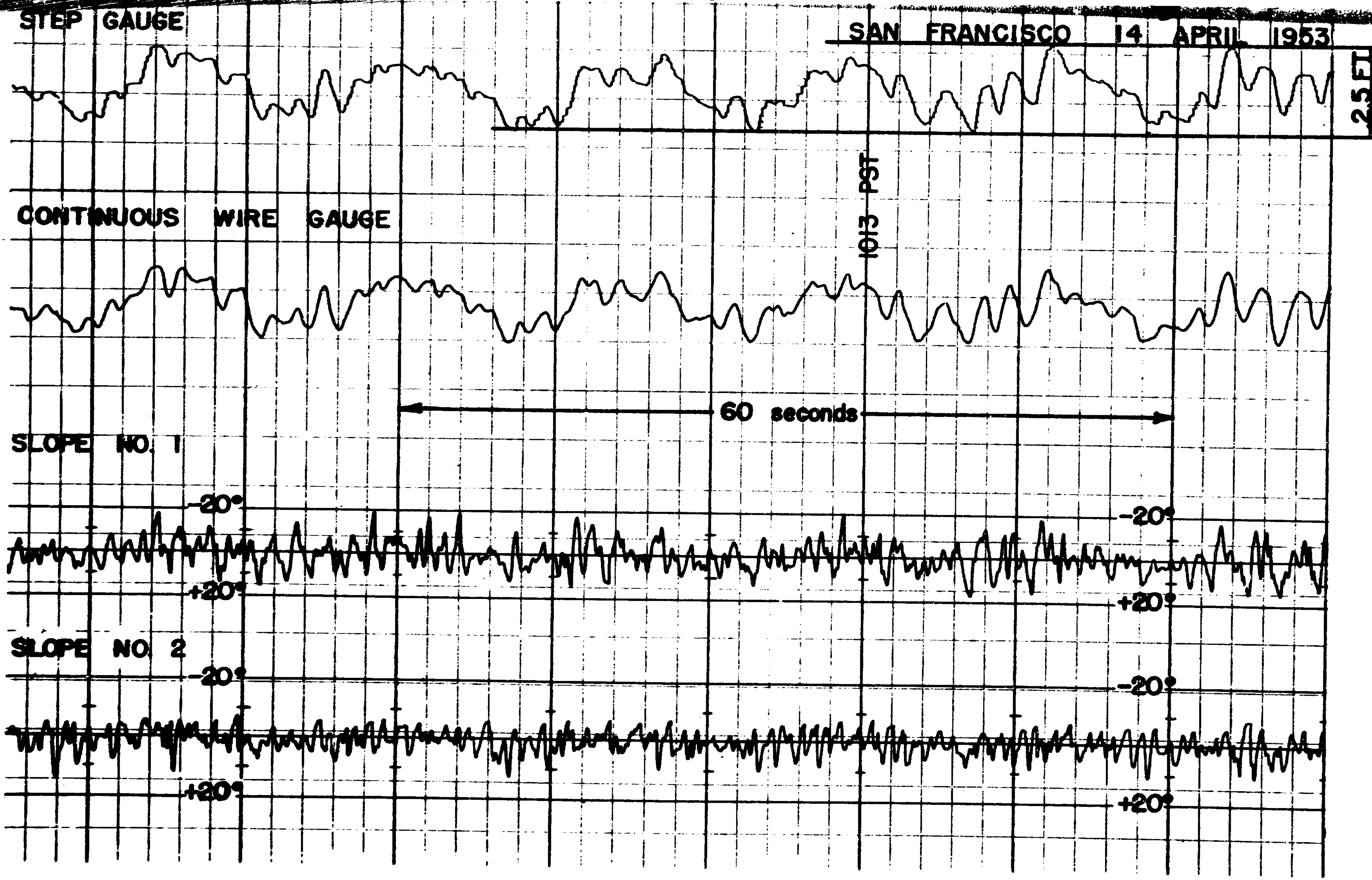
FIGURE 22



SIMULTANEOUS RECORDING OF STEP AND CONTINUOUS WIRE GAUGES

FIGURE 23

FIGURE 23



SIMULTANEOUS RECORDING OF STEP AND CONTINUOUS WIRE GAUGES

FIGURE 24

Figure 22 is a similar type of recording for an approximate two-minute period about 1103 PST on 8 April 1953. Maximum wave amplitudes have fallen to about one-half their values of 6 April although once again there is evidence in the no. 2 slope record, although much reduced in amplitude, of a fundamental period similar to that shown in the amplitude recording. The most interesting aspect of this data lies in the extensive high frequency variations on the amplitude traces. Although this condition is somewhat unusual, it is encouraging to note that the finite interval step recorder gave a record strikingly similar to that of the continuous-wire gage.

The data for 13 April given in Figure 23 show relatively small amplitude waves whose slopes, averaging perhaps 10 degrees from horizontal, are certainly as large and perhaps larger than those of the previously shown higher amplitude waves. The suggestion here is that relatively small waves of short wavelength are being driven by the wind, and that the sea surface has a definite choppy character. Reference to the observation log for 13 April reveals that wind at the piling at 0900 PST averaged 12 mph from WSW, with gusts to 15 mph; a few whitecaps were observed. In the early afternoon, gusts had increased to 20 mph from WNW at the piling; at Baker Beach it was definitely too windy for a balloon sounding to be made, and whitecaps were still visible. Note, too, the much reduced significant period in the amplitude records and the lack of any fundamental periodicity in the slope records.

In the case of the 14 April data (Figure 24), one can see smaller wind waves superimposed on a larger amplitude swell; occasional individual waves of $1\frac{1}{2}$ to 2 feet are observed, while swell amplitudes average about 2 feet. The generally larger slopes observed on the slope 1 record suggest that the preferred wave direction is more from the direction of Mile Rock than from northwest. Observations recorded in the log show a westerly wind 3 to 5 mph at the piling at 0915 PST, with no comment regarding whitecaps, nor regarding the visually observed swell direction.* In statistical terms, one might say that a large RMS value of slope indicates steep-sided waves; simultaneous large amplitude implies long wavelength, and vice versa for both. When RMS values of slope are the same for slope 1 and slope 2, waves are approaching in the mean from a direction midway between the two legs of the 3-wire slope array; when RMS values are significantly larger on slope 1 than on slope 2, then waves in the mean are approaching from a direction nearer to slope 1.

---

*As a rule, swell approached from the open water having a westerly to northwesterly direction, with the swell wave fronts finally becoming parallel to the beach. In this respect, the San Francisco light ship reported an essentially unvarying 270° as the direction from which swell was coming during the entire April observation period.

3. Comparison of the Step Gage and the Pressure Gage. Reference is again made to Figure 19 and the discrepancy in amplitudes given by the two gages. A brief exposition of the method of obtaining surface wave heights from subsurface pressure measurements will be given first. This method has been developed over a period of years at the University of California as part of an overall analysis of ocean wave records from submerged pressure gages [8]. The following equation is used to obtain the surface wave height:

$$H = \left[\frac{R}{100} \right] \left[\frac{C}{K} \right]$$

where H = wave height at surface, feet

R = EA chart reading of wave amplitude (from trough to succeeding crest), per cent of full scale.

C = full scale calibration constant for the instrument, in this case 5 feet.

K = pressure response factor based upon depth of instrument, depth of water at instrument, and length or period of wave being recorded.

The factor K is an important element in the calculation because it is variable with water depth and wave period, both of which are time-varying functions. The relation of the subsurface pressure fluctuations to the surface waves has been determined theoretically for two-dimensional, irrotational motion of an incompressible fluid in a relatively deep channel of constant depth. The response factor K therefore becomes the weak point in calculations of surface waves measured with pressure gages, because actual waves depart from a sinusoidal pattern. An error is inevitable, therefore, whenever an average or characteristic period is used to compute K, while the actual wave period is varying. The table of values of K for the Golden Gate installation (instrument 30 feet from bottom) indicates that for a water depth of 40 feet and a characteristic wave period of 10 seconds, the response factor K has the value 0.89. If the water depth remained at 40 feet and the period varied from 5 to 15 seconds, the factor K would change from 0.62 to 0.95, a total change amounting to 37% of the value at 10 seconds. If the period remained fixed at 10 seconds and the water depth varied from 37 to 43 feet, the factor K would change from 0.92 to 0.87. Were the variations in period and water depth to occur simultaneously and act in the same direction, K values would vary from 0.54 to 0.96, or about 50% of the value at 10 seconds and 40 feet. Since the chosen variations in both period and water depth are observed to occur, it is plain that the departure of waves from a sinusoidal pattern renders the method of computing surface waves from pressure gage measurements of doubtful value on the present theoretical basis.

In an effort to assess the nature of the departure of such computed waves from actual wave heights, the pressure gage and step gage records were compared. The initial comparison has been mentioned and is shown in Figure 19. However, to explore the discrepancy more fully, 20-minute intervals were chosen when both step gage and pressure gage records were available so that exactly the same groups of waves were available for comparison. Moreover, the records were carefully examined to the extent that identical waves were being compared, within the

limits of human error in comparing EA records with the Edin records. Due to the greater detail in the step gage water surface recordings, it was not possible to determine identical waves in both recordings where the amplitudes were below a level of the order of 1 foot. The results of the comparisons of these identical waves, for two 20-minute periods on the 24th and 25th of April, are shown in Figure 25. Here are plotted actual wave heights (from the step gage) against wave heights computed from the pressure gage record, using a different mean K for each of the two sets of pressure gage data. It is apparent that the wave heights computed from the pressure gage record are smaller than the actual waves by a large factor. An actual two foot wave, for example, is indicated by the pressure gage record to be in the order of $1\frac{1}{4}$ feet, and a four foot wave to be in the order of $2\frac{1}{2}$ feet, about 40% too low. The slopes of the two dashed lines are 1.9 and 1.3 respectively; a best-fitting mean curve would give a ratio of step gage height to pressure gage height of about 1.45. Moreover, the uncertainty of the computed wave height becomes larger for larger waves, as shown by the greater scatter of the points at the upper end of the plot. It is admitted that these data are limited in amount; however, it has been possible to compare wave heights, virtually wave for wave, possibly the first and certainly one of few times that such a comparison has been made. That these findings are not new to the oceanographer is illustrated in a paper by Folsom [3] where average factors ranging from 1.07 to values as high as 1.35 have been determined as necessary to correct observed pressure gage readings to obtain true water surface variations. Although it has not been possible to carry this phase of the analysis any further, a fairly complete selection of simultaneous step and pressure gage data is available for further study.

4. Reduction of Wave Gage Recordings Using Amplitude Probability Distributions.

a. Introduction

Any discussion or comparison of water wave sensing devices must also include an evaluation of the methods used in reducing the data and the extent to which the data reduction method gives meaningful and consistent results. Assuming a proper installation, the surface type gages give a direct and, limited only by the overall response time and amplitude sensitivity of the particular system, an accurate representation of the height variations of the water surface at a given point. As has been shown this is in contrast to the distorted surface wave reconstructions obtainable from subsurface sensing element recordings which result from physical limitations on the response of the sensing element and the lack of a more comprehensive theory of subsurface pressure recordings. For the time being, however, we lay aside considerations based on the quality of the recordings and investigate the procedures used to reduce the recorded time variations to some meaningful statistics. In this respect, it does not take much of a study to realize that the Snodgrass method of evaluating a characteristic period and an $H_{1/3}$ is not a satisfactory method of characterizing wave recordings. Both are arbitrarily determined parameters using only the well-defined waves in the recording and the contributions of the smaller amplitude higher frequency waves

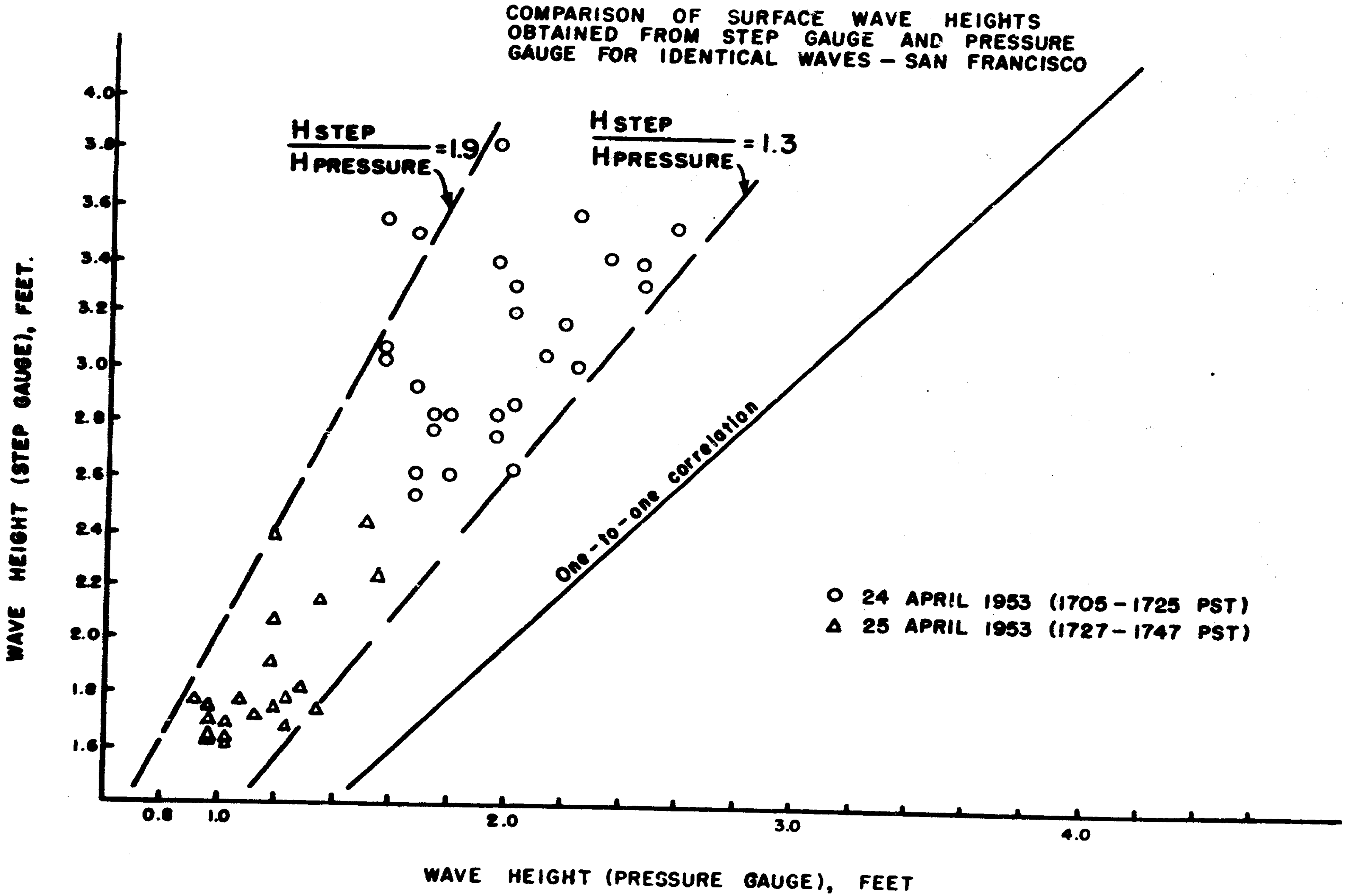

COMPARISON OF SURFACE WAVE HEIGHTS OBTAINED FROM STEP GAUGE AND PRESSURE GAUGE FOR IDENTICAL WAVES – SAN FRANCISCO
HSTEP / HPRESSURE = 1.9
HSTEP / HPRESSURE = 1.3
One-to-one correlation
○ 24 APRIL 1953 (1705 – 1725 PST)
△ 25 APRIL 1953 (1727 – 1747 PST)
WAVE HEIGHT (STEP GAUGE), FEET.
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0.8
1.0
2.0
3.0
4.0
WAVE HEIGHT (PRESSURE GAUGE), FEET

FIGURE 25

to the average value are thus ignored. In addition, there is generally an insufficient number of waves in the highest one-third number of waves in a 15-20 minute observation period to form a good statistical sample. More concisely, it may be stated that the Snodgrass method was designed to permit the relatively rapid computation of a mean period and amplitude which as a result of using only limited portions of the actual data are only approximations to the true values. The approximations become more valid as the wave recordings exhibit more uniformity in period and amplitude, but uniformity in such recordings is not the normal pattern. In its favor, it should be said that the method is relatively easy to apply to the filtered response of a subsurface pressure sensitive element and is not time consuming. Its applicability, however, varies directly with the range of frequencies present in the recording and the mere decision as to what constitutes a wave can be very difficult to make in the unfiltered response of a surface type sensing element. The desirable alternative to such a method of data reduction involves the evaluation of the mean parameters from complete frequency and amplitude spectra of the wave recordings. While the time required for manual computation of such statistics can seldom be justified, the rapidly increasing development of automatic computing mechanisms now permits the relatively painless and rapid determination of the desired spectra. Certain of the results of such analyses applied to the step gage recordings will be discussed in the succeeding sections.

b. Amplitude Probability Distributions

If a sufficiently long sample of the recorded continuous time variations of a sensing element is divided into a number of equally spaced time intervals each of which is significantly shorter than the minimum period present in the recorded data, and the corresponding amplitudes are plotted against their frequency of occurrence, an amplitude distribution is obtained which can be made arbitrarily close to that represented not only in the original sample but in the actual physical environment being sampled. Since amplitude distributions of water waves have been shown to follow the normal error curve [6], it is convenient to plot such distributions on normal error coordinates. In this manner, should the distribution be gaussian it is a relatively simple matter to determine from the best-fitting straight line, the root-mean-square (RMS = σ) values of the amplitude fluctuations from the fact that 68% (approx) of the points, i.e., from the 16% to 84% probability level, are within $\pm 1\sigma$ of the median (50%) value.

A series of such analyses for various samples of step gage data have been carried out by personnel of both the Applied Physics Laboratory and the Electrical Engineering Research Laboratory. At APL, manual evaluation of the amplitude probability distribution have been made using one second intervals for total sample periods of about four minutes. At EERL, evaluations were made from ten minute samples using an electronic device and curve following techniques which results in a series of dial readings representing the per cent of time the observed readings were above each of ten fixed (scale) levels. In all cases, chart readings were converted to wave height values in feet by using an average or representative calibration involving the number of 0.2 foot steps per chart division.

Examples of several of the APL evaluations are shown in Figures 26 through 29. The first of these is representative of most of such distributions in showing essentially linear characteristics. Among the exceptions to these linear or gaussian distributions are those represented in Figures 27-29 all of which occurred during the relatively high wave period from 17-25 April. The distribution in Figure 27 is linear with the exception of values near the upper and lower probability levels. Such an effect is undoubtedly due to the fact that the sample was too short to be representative of the normal wave pattern in particular as regards the very low and very high amplitude waves. Somewhat more serious discrepancies can be observed in Figures 28 and 29 and a little more thorough discussion of this situation is felt to be warranted. Although there are two factors which could have been responsible for these observed non-gaussian distributions i.e., non-linearity in the step gage itself and the complex oceanography of the channel, a significant part of the effect is again felt to be the result of taking samples too short to be representative of the actual water surface variation. That there was some non-linearity in either the amplifying or recording circuits of the step gage is evident from an examination of the recorded data, i.e., full scale pen motion on the chart might give rise to a calibration shift ranging from seven 0.2 foot steps per major chart division at the low end of the chart to nine to ten 0.2 foot steps per division at the upper end. However, the effect should only be significant for the very highest waves and if important should have shown up on all amplitude distributions made during high wave periods. Such was not the case.

The effect of the complex oceanography is more difficult to evaluate and it may well have been that the combination of a regular surge type variation with the normal gaussian distribution of water waves could have given rise to non-gaussian distributions. Since surge effects were apparently present a relatively small per cent of the time, their contribution to a non-gaussian distribution is felt to be very limited. It was not possible either to make a one-to-one correlation between surge appearances and the non-gaussian cases. It should be noted in this respect that a series of longer (10 minute) EERL analyses of data samples taken during the high wave period all showed consistent gaussian distributions. However, when the longer analyses were made for the same times at which the APL analyses showed serious non-gaussian distributions, the non-linear effects were not entirely eliminated. Thus while there can be no doubt as to the reality of an occasional non-gaussian wave amplitude distribution for this location, the effect is certainly reduced when longer samples are taken.

An additional step can now be made after obtaining the σ values. Pierson [6] has recently shown the following relationships to be valid for a gaussian distribution of wave amplitudes:

$$H_{1/3} = 4\,\sigma$$

$$H_{1/10} = 5.1\,\sigma$$

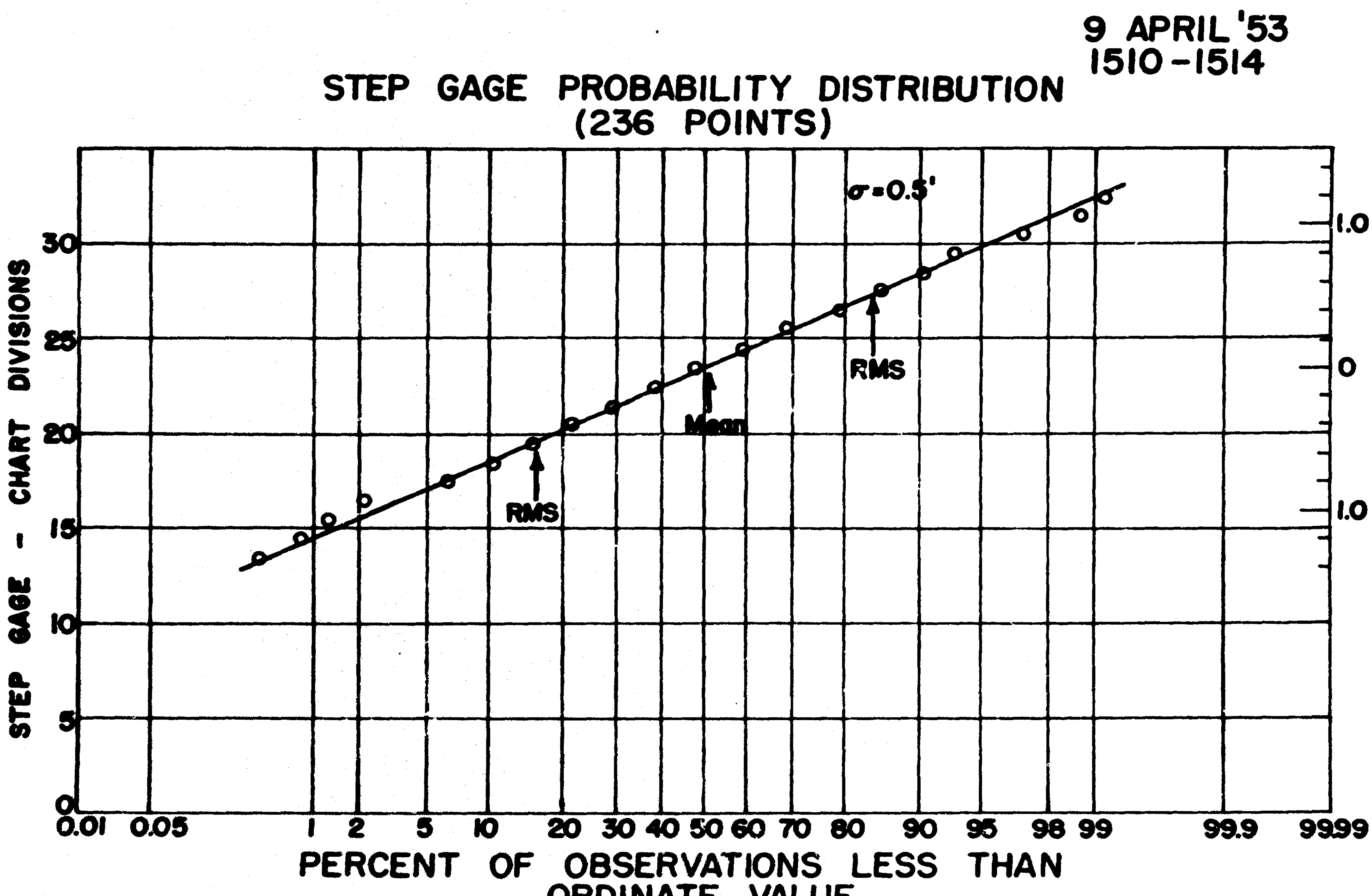

9 APRIL '53
1510 - 1514
STEP GAGE PROBABILITY DISTRIBUTION
(236 POINTS)
σ = 0.5'
RMS
Mean
RMS
STEP GAGE - CHART DIVISIONS
0
5
10
15
20
25
30
SCALE CALIBRATION IN FEET
1.0
0
1.0
0.01
0.05
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.9
99.99
PERCENT OF OBSERVATIONS LESS THAN ORDINATE VALUE

FIGURE 26

24 APRIL '53
1111 - 1115

STEP GAGE PROBABILITY DISTRIBUTION
(320 POINTS)

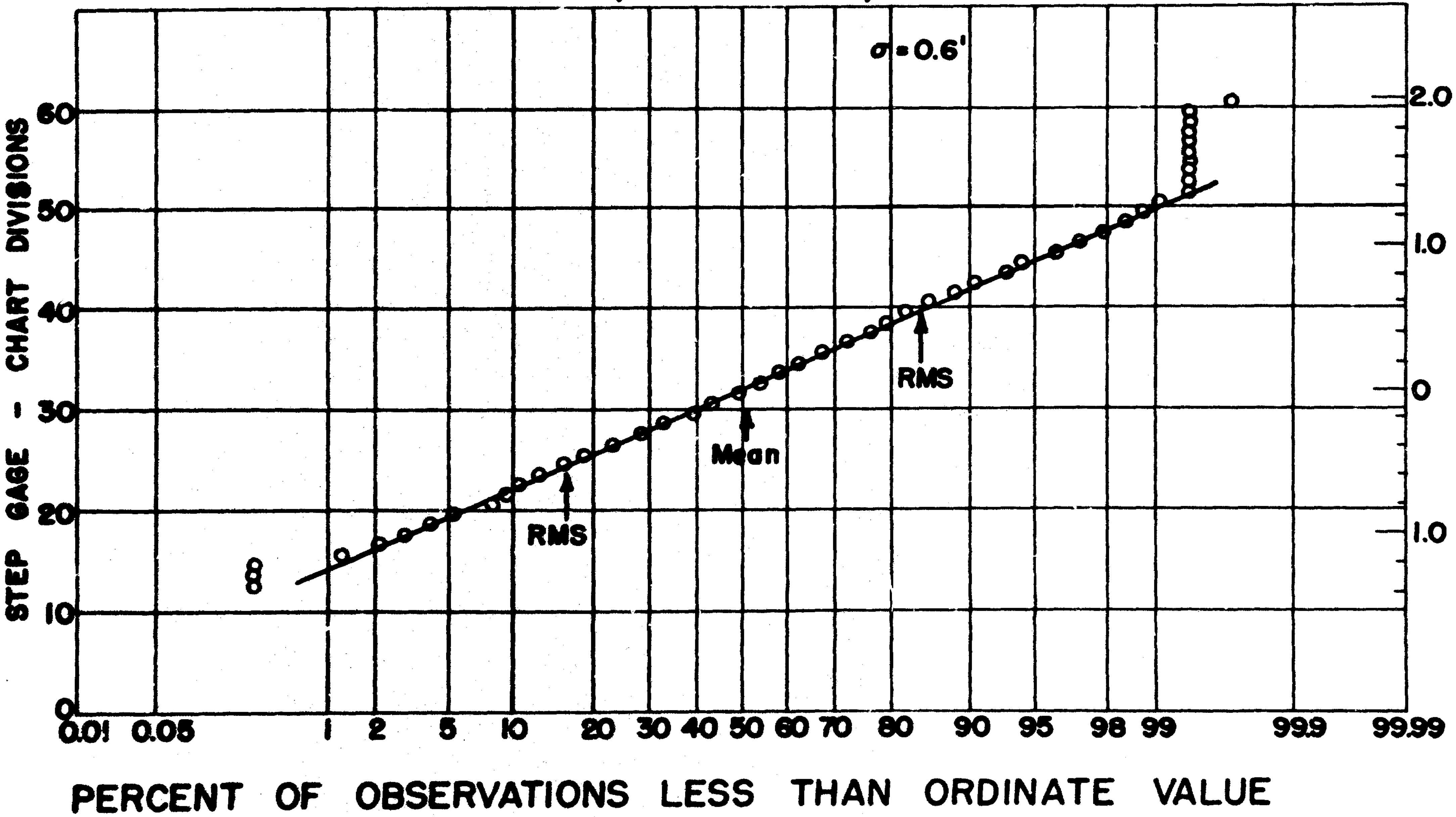


FIGURE 27

1413 - 1417

STEP GAGE PROBABILITY DISTRIBUTION
(335 POINTS)

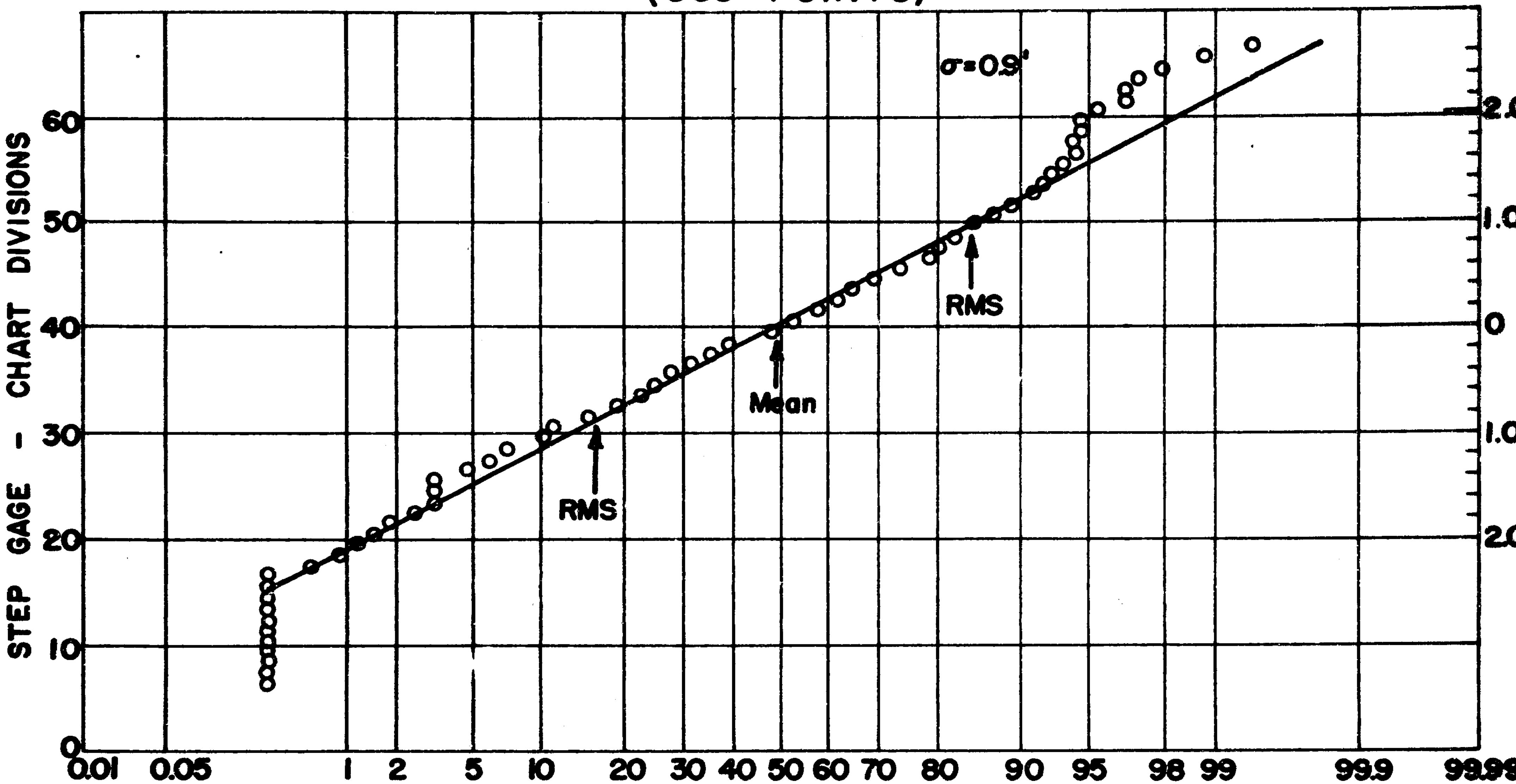


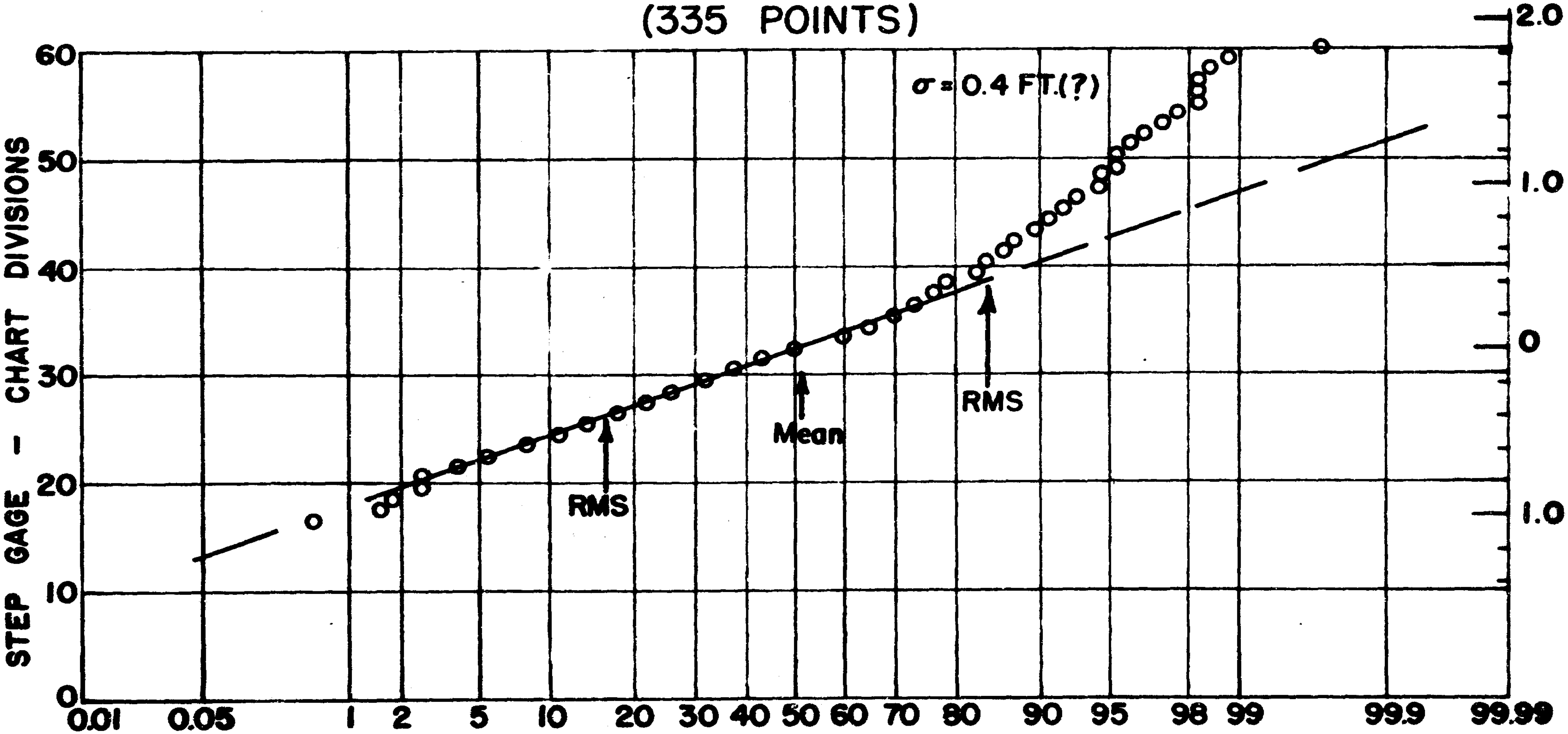
FIGURE 28

24 APRIL '53
1347 - 1351

STEP GAGE PROBABILITY DISTRIBUTION

24 APRIL '53
1347 - 1351

STEP GAGE PROBABILITY DISTRIBUTION
(335 POINTS)



PERCENT OF OBSERVATIONS LESS THAN
ORDINATE VALUE

FIGURE 29

Table 5 gives the σ and $H_{1/3}$ values derived from all computed amplitude probability distributions of step gage data. One or two observations might well be made. Since the computed points of the amplitude distribution plot exhibit some scatter about a best-fitting line, some judgement is necessary in drawing that line and the resultant slope or σ values may be in error by as much as ± 0.05-0.1 foot. The resultant four-fold increase in this value for $H_{1/3}$ is partially reflected in the rather large range of $H_{1/3}$ values that are reported for any one day although there is no doubt but what the greater part of this variation is real. Great care would certainly have to be taken in choosing a data sample of several minutes duration as being representative of the water surface for periods of several hours even if the mean amplitude were to exhibit no time variation.

Two further comparisons can now be made. Although only some dozen 15-20 minute samples of step gage data were analyzed by the Snodgrass method, it was felt that a comparison of these $H_{1/3}$ values with those computed from corresponding 10 minute samples involving the 4σ relationship might be interesting. One would be led to expect that the Snodgrass $H_{1/3}$ values should be somewhat larger as a result of their not using the total of all waves in the computation. These data are shown in Table 6 and with the one exception of April 22, the Snodgrass determined $H_{1/3}$ values are of the order of 10% larger than the amplitude distribution determined values. Although no one factor can be singled out as causing the discrepancy for this date, several smaller effects which would normally cancel each other have all added up in the same direction. These include (1) the use of a scale calibration in the probability method from one well-defined wave that was larger than the average scale calibration used in the Snodgrass method, (2) a greater than normal superposition of high frequency variations on the crests and troughs of the wave recording in such a manner as to reduce wave crest-to-trough differences, and (3) a somewhat reduced mean amplitude of waves in the five minute period, 1013-1018, not covered by the amplitude distribution analysis.

A final comparison of all pressure gage and step gage computations for $H_{1/3}$ is given in Figure 30. No points were used unless both evaluations had been made within no more than 10-15 minutes of each other and the step gage data have been divided into two subdivisions according to the Snodgrass or amplitude distribution methods of computation. Once again with a very few exceptions, we can see that step gage values are consistently higher than pressure gage values. The slopes of the two bracketing lines are 1.12 and 1.52 respectively and a figure about 1.3 would be a fair average. Once again, too, we note that while the overall range in the two values becomes larger with larger waves, there is a tendency for greater distortion in the pressure gage readings for low amplitudes. This effect is certainly not unreasonable since waves below a certain critical frequency would be damped out entirely in the pressure sensing unit.

c. Frequency Spectra Comparisons

Since a much more comprehensive analysis of the power spectra of the water surface variations and of their comparisons with associated radio recordings will be made in a subsequent report, it will be sufficient to state here

TABLE 5

$H_{1/3}$ EVALUATIONS FROM STEP GAGE AMPLITUDE PROBABILITY DISTRIBUTIONS

DATE	TIME	RMS or σ (Feet)	$H_{1/3} = 4\sigma$ (Feet)
Feb. 19	1411-1415	0.8	3.2 *
Feb. 20	1210-1214	0.8	3.2 *
Apr. 6	1041-1051	0.76	3.04 **
	1123-1133	1.01	4.04 **
	1430-1440	0.94	3.76 **
	1450-1500	1.21	4.84 **
	1626-1636	1.07	4.28 **
	1734-1744	1.06	4.24 **
Apr. 7	1246-1256	0.56	2.24 **
	1252-1302	0.65	2.60 **
	1332-1342	0.63	2.52 **
	1418-1428	0.62	2.48 **
	1548-1558	0.68	2.72 **
Apr. 8	1356-1406	0.71	2.84 **
	1505-1515	0.61	2.44 **
	1600-1610	0.79	3.16 **
	1618-1628	0.63	2.52 **
Apr. 9	1439-1443	0.5	2.0 *
	1510-1514	0.5	2.0 *
Apr. 10	1140-1144	0.3	1.2 *
	1228-1232	0.4	1.6 *
	1306-1310	0.5	2.0 *
	1348-1352	0.4	1.6 *
	1430-1434	0.5	2.0 *
	1515-1519	0.4	1.6 *
Apr. 11	1024-1028	0.5	2.0 *
	1128-1132	0.6	2.4 *
	1344-1348	0.4	1.6 *
Apr. 13	1525-1535	0.28	1.12 **
Apr. 14	1358-1362	0.4	1.6 *
	1608-1618	0.27	1.08 **
Apr. 15	1136-1140	0.4	1.6 *
	1336-1340	0.4	1.6 *

TABLE 5 (Continued)

DATE	TIME	RMS or σ (Feet)	$H_{1/3} = 4\sigma$ (Feet)
Apr. 16	1137-1147	0.30	1.20**
	1405-1409	0.5	2.0 *
	1457-1461	0.5	2.0 *
Apr. 17	1251-1255	1.0	4.0 *
	1343-1347	0.7	2.8 *
	1435-1439	0.6	2.4 *
	1520-1524	0.9	3.6 *
Apr. 18	1251-1255	0.6	2.4 *
	1349-1353	0.6	2.4 *
	1450-1454	0.5	2.0 *
	1531-1535	0.7	2.8 *
Apr. 20	1034-1044	0.40	1.60**
	1351-1401	0.72	2.88**
	1552-1602	0.79	3.16**
Apr. 21	1114-1118	0.7	2.8 *
	1122-1126	0.7	2.8 *
	1446-1450	0.7	2.8 *
Apr. 22	1003-1013	1.20	4.80**
	1031-1035	0.7	2.8 *
	1121-1125	0.6	2.4 *
	1345-1349	0.9	3.6 *
	1413-1417	0.9	3.6 *
	1525-1529	0.9	3.6 *
	1536-1540	1.0	4.0 *
	1543-1553	0.97	3.88**
Apr. 23	0937-0947	0.65	2.60**
	1016-1026	0.62	2.48**
	1046-1050	0.5	2.0 *
	1121-1125	0.4	1.6 *
	1137-1147	0.64	2.56**
	1315-1319	0.9	3.6 *
	1410-1414	0.7	2.8 *
	1454-1458	0.9	3.6 *
	1539-1543	0.8	3.2 *
	1554-1604	0.72	2.88**
	1633-1643	0.86	3.44**
Apr. 24	1007-1017	0.51	2.04**
	1035-1039	0.6	2.4 *
	1042-1052	0.57	2.28**
	1111-1115	0.6	2.4 *

TABLE 5 (Continued)

DATE	TIME	RMS or σ (Feet)	$H_{1/3} = 4\sigma$ (Feet)
Apr. 24	1148-1152	0.5	2.0 *
	1347-1351	0.4	1.6 *
	1500-1510	0.48	1.92**
	1705-1715	0.56	2.24**
Apr. 25	0947-0957	0.34	1.36**
	1005-1009	0.5	2.0 *
	1100-1110	0.30	1.20**
	1446-1456	0.23	0.92**
	1530-1534	0.3	1.2 *
	1727-1737	0.33	1.32**
Apr. 27	1513-1523	0.62	2.48**
Apr. 28	1023-1027	0.7	2.8 *
	1230-1234	0.7	2.8 *

* Four minute APL values (manual computation)

** Ten minute KERL values (automatic computer)

TABLE 6

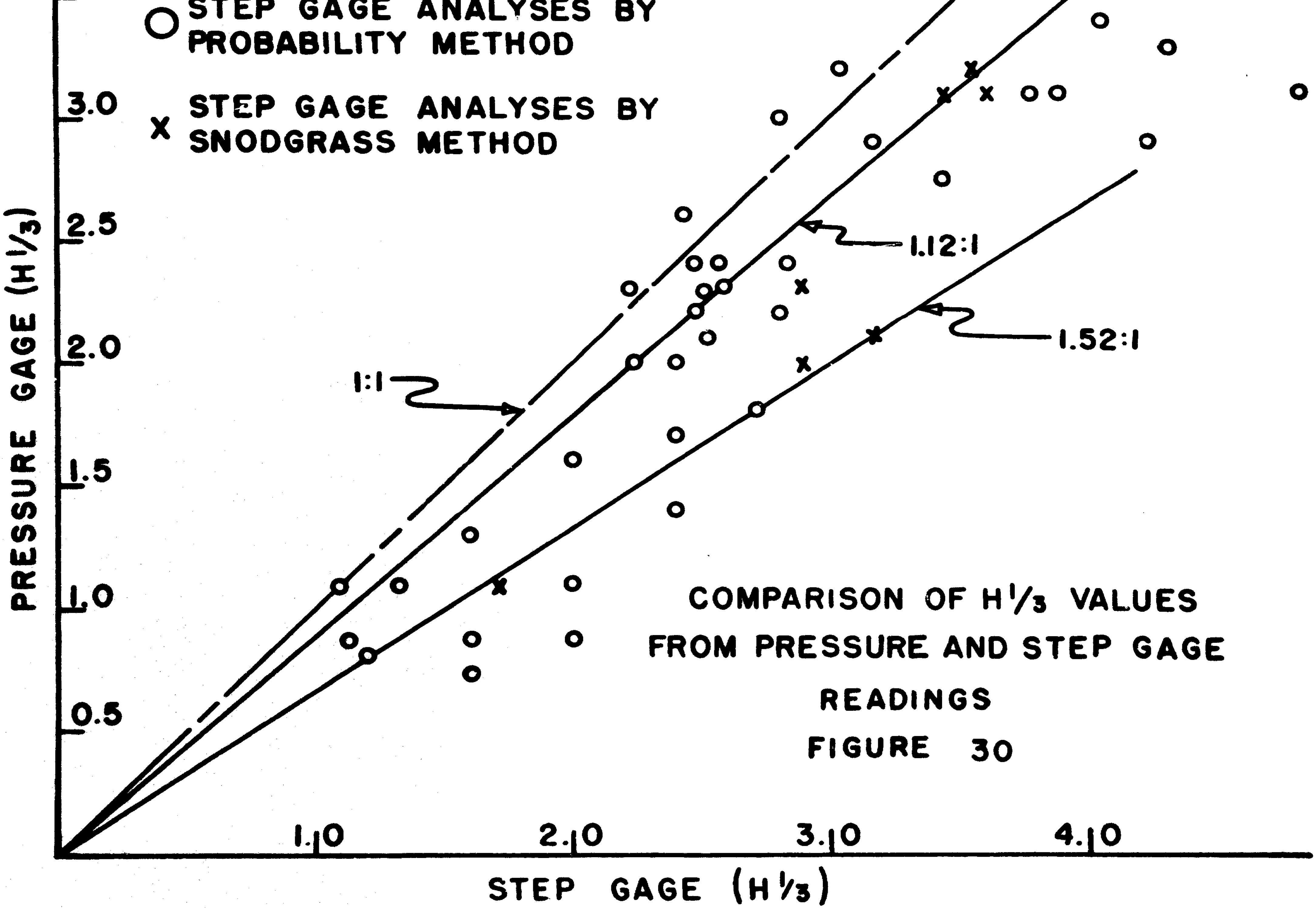
COMPARISON OF $H_{1/3}$ VALUES OBTAINED BY SNODGRASS AND PROBABILITY

DISTRIBUTION METHODS FOR STEP GAGE DATA

DATE	TIME (Snodgrass)	TIME (Probability)	$H_{1/3}$ (Snodgrass) (1)	$H_{1/3}$ (Probability) (2)
April 6	1041-1101	1041-1051	3.55	3.04
April 7	1331-1348	1332-1342	2.89	2.52
April 8	1600-1620	1600-1610	3.17	3.16
April 20	1351-1408	1351-1401	2.90	2.88
April 22	1003-1018 1543-1558	1003-1013 1543-1553	3.45 3.60	4.40 3.88
April 23	1016-1032 1554-1610	1016-1026 1554-1604	2.55 3.20	2.48 2.88
April 24	1042-1058 1705-1725	1042-1052 1705-1715	2.41 2.90	2.28 2.24
April 25	1100-1115 1727-1747	1100-1110 1727-1737	1.65 1.71	1.20 1.72

*10 minute EERL values

Average ratio (1)/(2).......1.04
Average radio (1)/(2) omitting April 22.......1.12



COMPARISON OF $H^{1}/_{3}$ VALUES FROM PRESSURE AND STEP GAGE READINGS

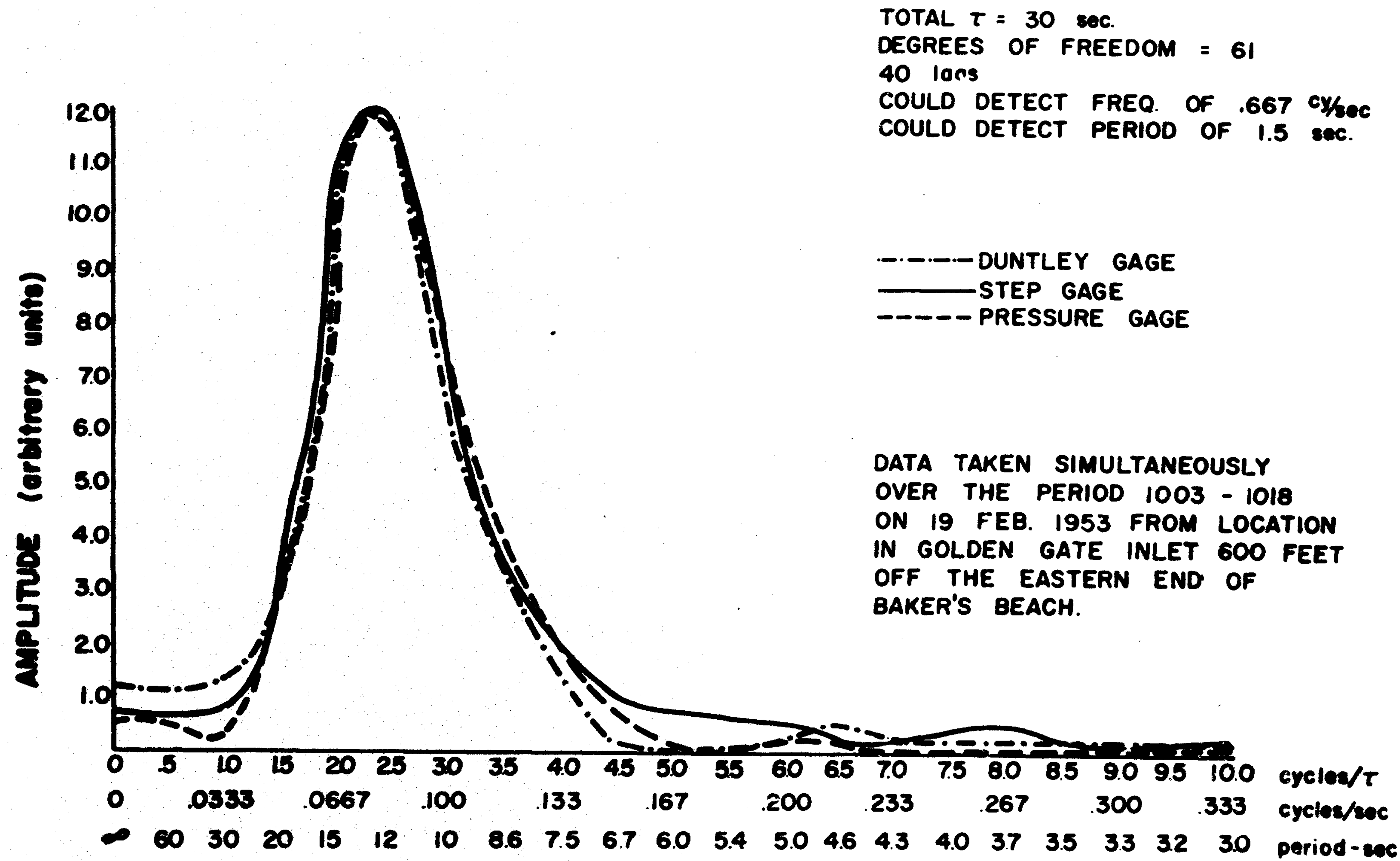
FIGURE 30

that there was never any significant discrepancy between either an average wave period or a complete power spectrum for the different wave sensing elements. An example of this effect is shown in Figure 31 which shows the nearly identical power spectra obtained during a twenty minute period on 19 February in which step, pressure and continuous-wire recordings were being made simultaneously. Naturally, the evaluation of a power rather than a frequency spectrum reduces the importance of the higher frequency filtering action of the subsurface gage, but it is nevertheless true that the neglect of the high frequency components and a moderate amplitude distortion has little effect on the power spectrum of a variation having average periods considerably larger than those being filtered.

d. Motion Picture Recordings

A further attempt to study some of the higher frequency wind waves and the extent to which they might be masked by the step gage was made by using direct motion picture photography of the step gage itself. While the few analyses made of this data showed excellent correlation with the step gage output, the nearly vertical camera angle employed in making the pictures made it impossible to interpolate values of the water surface between the levels of the sensing contacts on the gage.

LENGTH OF DATA - 15.43 min.
TOTAL T = 30 sec.



POWER SPECTRUM OF WATER SURFACE VARIATIONS
FIGURE 31

APPENDIX A

The Continuous-Wire Wave Gage

The method developed at this Laboratory* for the continuous measurement and recording of ocean wave heights is shown schematically in Figure 32. M is a heavy stainless steel vertical mast attached rigidly to a specially constructed piling at the point where ocean wave data are desired. Supported by the mast is a vertical 17 ft. length of resistance wire RW, insulated at its upper end by insulator G and fastened securely at its lower end to support arm A. Wire RW is always partially immersed in the ocean water, as may be seen from the indicated locations of the "low low" and "high high" water lines. Figure 33 shows a horizontal section of the mast and the location of the sensing wires.

Electrical components in the sketch are the generator E, voltmeter V, and resistor R. When the resistance value of R is chosen sufficiently high an essentially constant current, independent of water level, flows through R and through the resistance wire at all times. This constant current (denoted by I) results in a potential drop V made up of the following components (see sketch) (1) a potential drop V_1 along the exposed portion of the wire, (2) a drop V_2 from the point of emergence of the wire to the point of emergence of the mast, and (3) a drop V_3 along the exposed portion of the mast. By choosing an appropriate combination of resistivity and diameter for the sensing wire RW (see Figure 32 for wire data) and by establishing a minimum immersion depth of at least 3 feet, the potential V_2 is rendered negligible in ocean water of average salinity. V_3 is also negligible since the resistance per unit length of mast is so very much less than that of the resistance wire itself. We are left then with the simple fact that the voltmeter indication V is substantially the drop along the resistance wire alone and hence is (1) closely proportional to the length d of exposed wire and (2) is linearly related to ocean wave height. It is this last result that forms the modus operandi for the wave gage, the principal requirements being (1) that the generator voltage E, the resistor R, and the sensing wire properties remain invariant with time and (2) that the recording voltmeter have a stable (and preferably linear) deflection characteristic. A further matter of concern in some situations is in regard to the lag coefficient of the recording system — this must of course be appropriately small if accurate delineation of wave detail is desired. It is also essential that the sensing wire be of uniform gage throughout its length.

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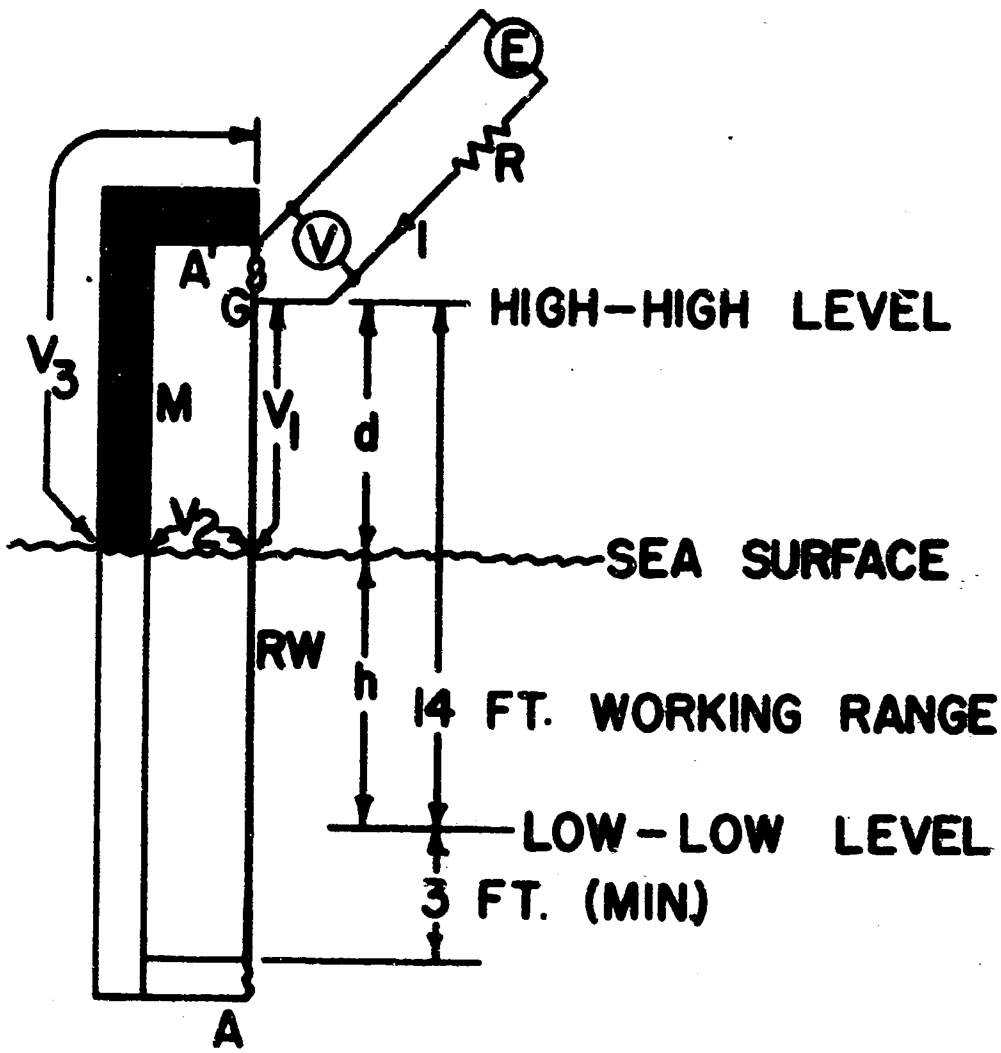
*The system herein described made use of the general features of a continuous-wire type gage developed by Duntley and described in detail in a memorandum to Guy Worsley from I. Katz (JHU/APL) dated 24 July 1952.



MAST M IS STAINLESS STEEL PIPE, $1\frac{1}{2}''$ I.P.S.

WIRE RW IS STAINLESS STEEL (A.I.S.I. NO. 303) AND IS $\frac{1}{16}''$ IN DIAMETER.

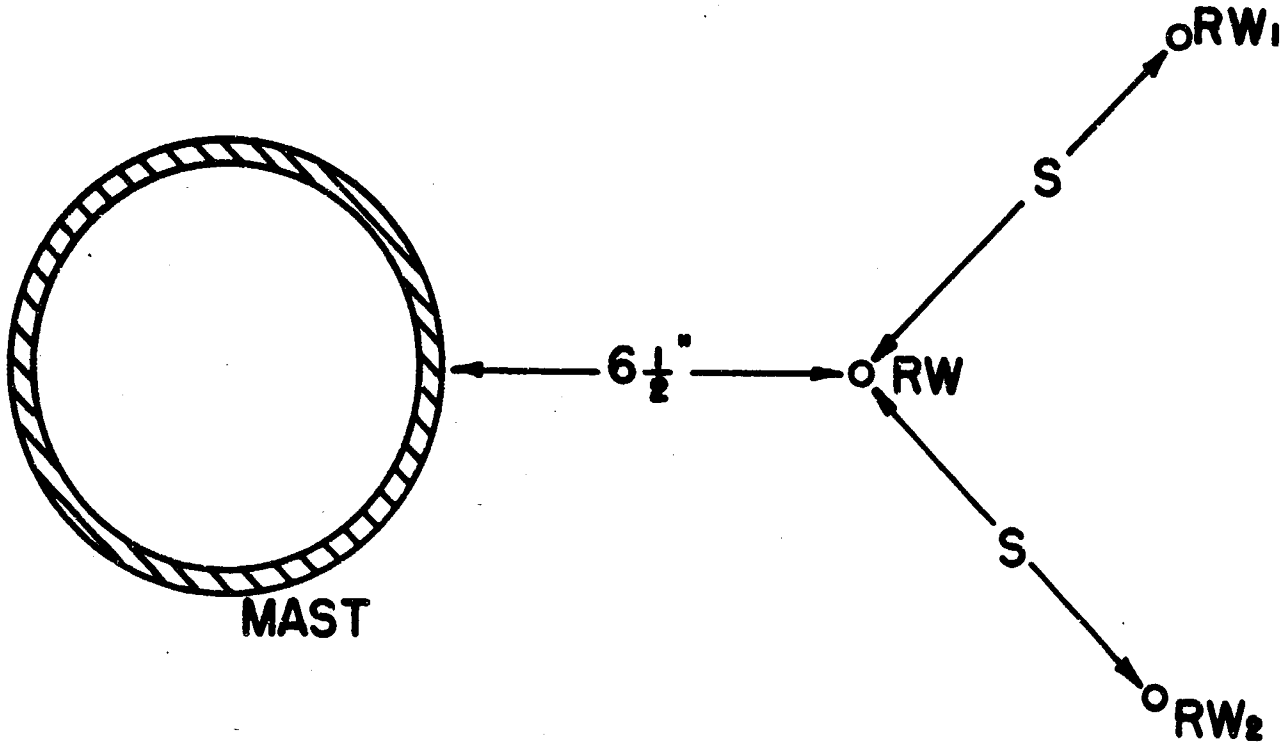
RESISTANCE PER FOOT: 0.115 OHM

$E \cong$ 25 VOLTS RMS., FREQUENCY — 2000 CPS.

$R \cong$ 150 OHMS

CONTINUOUS-WIRE WAVE GAGE METHOD OF MEASURING WATER WAVES

FIGURE 32



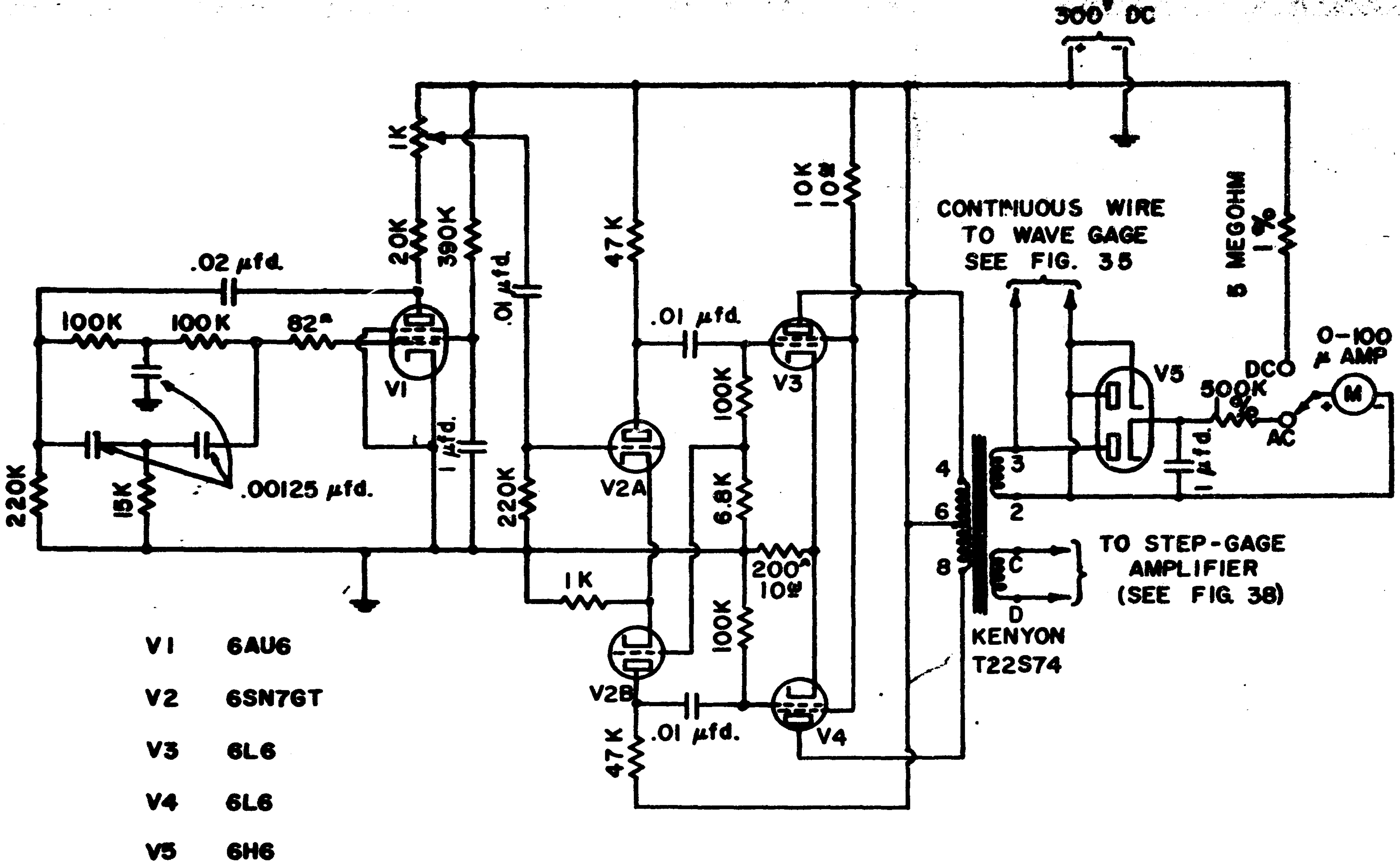
HORIZONTAL SECTION SHOWING DISPOSITION OF MAST AND SENSING WIRES.

FIGURE 33

Having established in general terms a method for the measurement of ocean wave heights, a host of practical engineering problems are immediatcly confronted when one attempts to physically embody the method. In the first place, no environment to be found in nature seems quite so inimical to scientific apparatus as the open sea. The measuring current I, for example, must not have a direct (d.c.) component if electrolytic destruction of the sensing wire is to be avoided. Alternating current is thus necessary and a very high frequency is reported to be beneficial in minimizing the effects of wire contamination. Too high a frequency, however, introduces difficulties in the electrical measurements and in addition the electrical flow in the sea water is then no longer a simple diffusion process. The necessity for energizing the electrodes via a 2300 foot marine cable also imposed an upper limit to the frequency. As a compromise, a frequency of 2000 cycles was used and appeared completely satisfactory. For the Golden Gate measurements, as viewed in retrospect, a frequency of 400 cycles might have been about as satisfactory and would have yielded the marked advantage that commercially available 400 cycle power generating and regulating apparatus could have been utilized. The amplitude of E should be high (we used about 25 volts) so that V can easily be measured even in the presence of substantial interference. Electronic means were used for generating and controlling the voltage E, and a manual adjustment was provided for resetting. These employed certain well-established electronic techniques which have the demonstrated virtues of being simple yet highly effective. Figure 34 shows the circuit schematic of the 2000 cycle electronic power generator, consisting of oscillator V1, phase inverter V2, power amplifier V3 and V4, and output indicator rectifier V5.

Measuring and recording of the voltage V also made use of electronic means, and more or less conventional amplifying techniques were employed here. The circuit for these is shown schematically in Figure 35 and comprises: (1) a conventional triode amplifier V6, (2) a cathode follower V7, and (3) a rectifier (V8-V9) of the voltage-doubling type. The bulk of the amplification was obtained with a commercial recording amplifier manufactured by the Edin Company, which company also supplied the recorder itself. This latter was a fairly high speed instrument, considerably more rapid in response than was actually needed. It provided a maximum trace width of 40 mm, and a paper speed adjustable in 9 steps from 0.25 to 100 mm/sec.

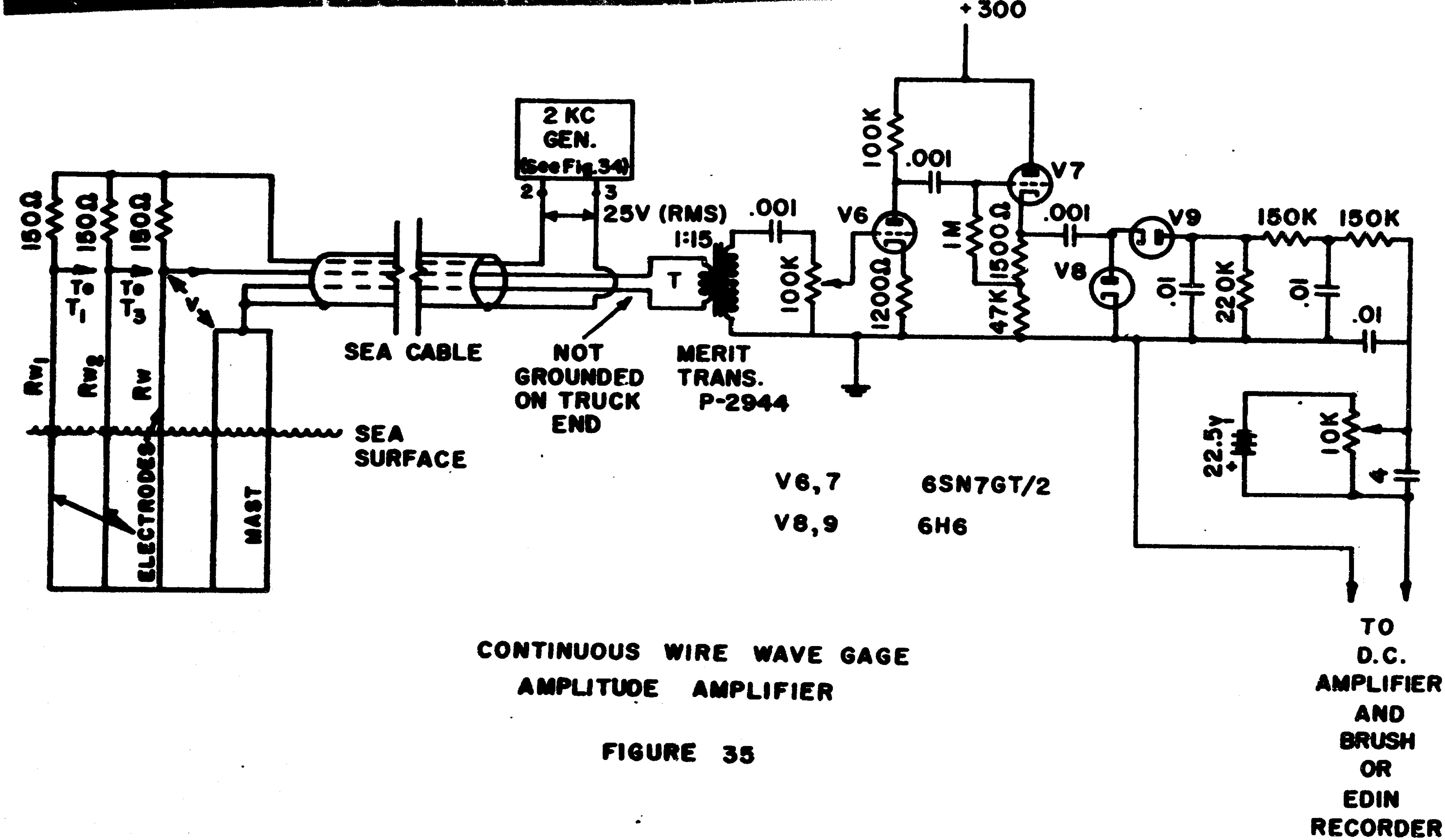
Calibration of the ocean wave gage was given a great deal of thought, mainly with the view of working out a direct system wherein simultaneous observations of actual water level and of recorder indication could be paired for future use in translating ocean wave recordings into terms of wave heights. After considerable preliminary study a practicable system was still being worked out when the problem was suddenly and completely resolved by our decision to incorporate a step-type wave gage (see Appendix B) into the structure supporting the sensing wire. The step-type wave gage, or step gage as it is called, is inherently self-calibrating for changes in water level, and automatically and continuously provides us just those datum points which are needed -- i.e., those in actual use at any given time. In short, it provides a nearly ideal calibration system, and reduced the calibration problem to the much simpler one of providing adequate long term stability so that frequent calibration checks are not required.



WIRING DIAGRAM OF 2 KC POWER GENERATOR

FIGURE 34

+300



CONTINUOUS WIRE WAVE GAGE
AMPLITUDE AMPLIFIER

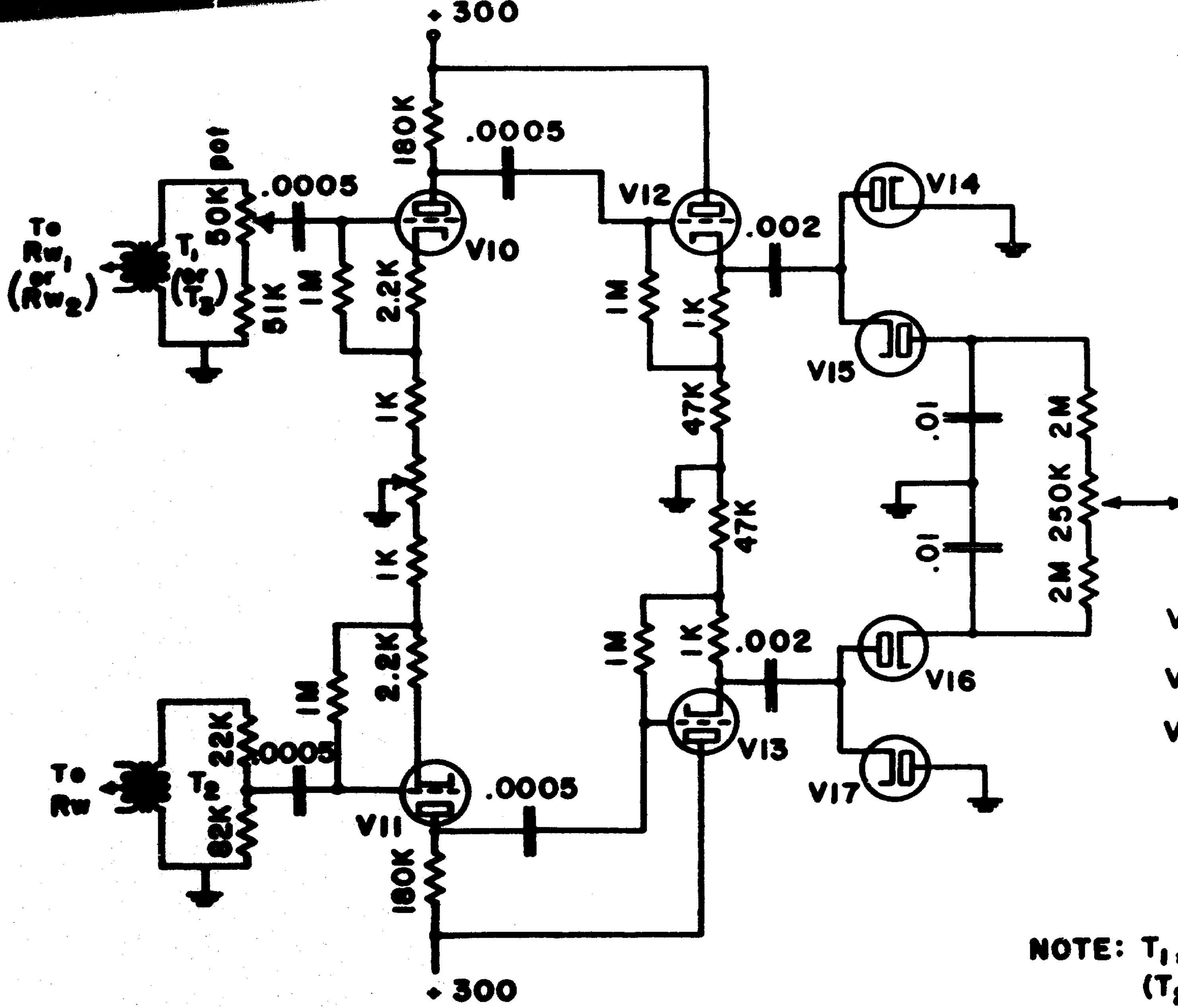
FIGURE 35

In order to gain further insight into the reflection of radio waves from an undulating sea surface it was desired to measure and record, as a function of time, not only wave amplitudes but also wave slopes. Here we are using the term slope synonymously with gradient in the sense that it is a two-dimensional vector having orientation as well as magnitude. To accomplish slope measurements, we used in addition to the apparatus already described, two more vertical sensing wires, each energized from the same source (E, Figure 1) and each having its own series resistor R. The three sensing wires were disposed as in Figure 33.

Corresponding to the voltage V derived from the amplitude sensing wire RW, let us use V' and V'' to denote the potential at the sensing wires RW_1 and RW_2. It is evident, then that if the calibration coefficients of the three systems are identical, V - V' and V - V'' will be proportional respectively to the components of the gradient in the directions VV' and VV''. It is this result that forms the theoretical basis of the slope measurement. To put it into practice all that was required was to arrange electronic equipment with suitable subtracting circuits and simply record the quantities V - V' and V - V''. The circuitry employed to accomplish this is shown in schematic form in Figure 36. Transformers T_1 (or T_3) and T_2 in this figure connect via the sea cable to the electrode wires RW_1 (or RW_2) and RW. Each transformer feeds a cascade arrangement including a triode amplifier (V10 and V11), cathode follower (V12 and V13), and rectifier (V14/15 and V16/17). By differentially connecting the latter, as shown, a D-C voltage proportional to the difference V - V' (or V - V'') is obtained. This is then amplified and recorded by the Edin equipment.

In actual operation certain difficulties were encountered that proved rather serious in dealing with small gradients. Application of the conversion factor to V - V' and V - V'' is, superficially at least, a perfectly straightforward means of arriving at the corresponding height differences but it was observed in practice that whereas we should have had V - V' = V - V'' = 0 for a horizontal sea surface at all height levels, small residuals of random sign appeared which tended to mask the effect of very small height differentials. These residuals were attributed to slight differences in the dynamic characteristics of the three amplifiers handling V, V' and V'' and were most troublesome at low water levels where the largest electrode voltages were obtained. This situation was considerably improved by increasing the separation to 6 inches, although at the expense of detail.

Calibration of the slope indicators was performed by replacing the wave gage electrode system and its associated sea cable with a network designed to simulate the actual installation. By appropriate variations in the resistors simulating the electrode wires it was possible to calibrate the equipment in terms of its response to various combinations of amplitude and slope. No direct checks on the accuracy of this procedure were made owing mainly to the impracticability of reproducing, even crudely, the various degrees of steepness found in the actual ocean waveforms. We are confident, however, that the accuracy of the slope recordings is adequate for the intended use, this statement of course being subject to the limitations discussed in the previous paragraph.



V10, 11	12AX7/2
V12, 13	12AT7/2
V14, 15, 16, 17	6AL5/2

NOTE: T_1, T_2, & T_3, are Merit P-2944
(T_2 is actually T of Fig. 35)

CONTINUOUS WIRE WAVE GAGE SLOPE AMPLIFIER

FIGURE 36

APPENDIX B

The Step Wave Gage

As a complement to the continuous type of wave amplitude recorder described in Appendix A, a second type of gage was also used for the measuring and recording of wave amplitudes. Like the continuous gage, it operated on purely electrical principles and shared with it the marked advantage of having no moving parts other than those in the recorder itself. Figure 37 shows the essential elements involved.

Electrodes E_1, E_2 ------- E_{71} are automobile-type spark plugs inserted into the mast at 2.4 inch (0.2 foot) intervals along the 14-foot working range. The interior of the mast is hermetically sealed off from the environing sea and the entrapped air maintained at a pressure of about 60 lbs./sq. inch (absolute). This was intended as a protection to the resistors and the wiring within the mast.

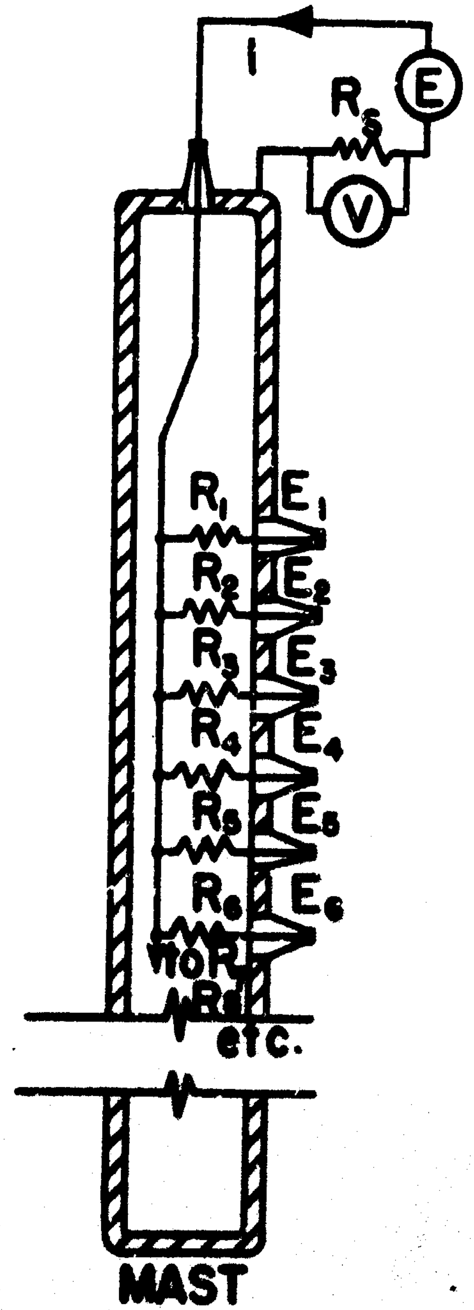
Each of the electrodes, when covered by rising sea water, provides a closed circuit between its associated resistor and the mast M. Resistors R_1, R_2 --- R_{71} are all identical, their nominal value being 4700 ohms. This was selected as being low enough to be negligible compared to the very high electrode-to-mast resistance obtained when the electrodes are not immersed, yet high enough that when the electrodes are immersed, the electrode-to-mast resistance is itself then negligible compared to the 4700 ohms. In other words, with the value chosen for R_1 --- R_{71}, the action of the rising and falling sea water is essentially the same as that of closing and opening an ideal switch.

E in Figure 37 is a constant-voltage generator of frequency 2000 cps and amplitude 1 volt. R_s is a shunt of negligible resistance and voltmeter V is, in effect, simply an indicator of generator current I. This current being the sum of the individual currents delivered to the immersed electrodes, we have

$$I = \sum \frac{E}{R_i} .$$

However, the R_i's are all equal to 4700 ohms and so this simplifies to

$$I = \frac{E}{4700} \times N$$



SCHEMATIC DIAGRAM OF STEP WAVE GAGE

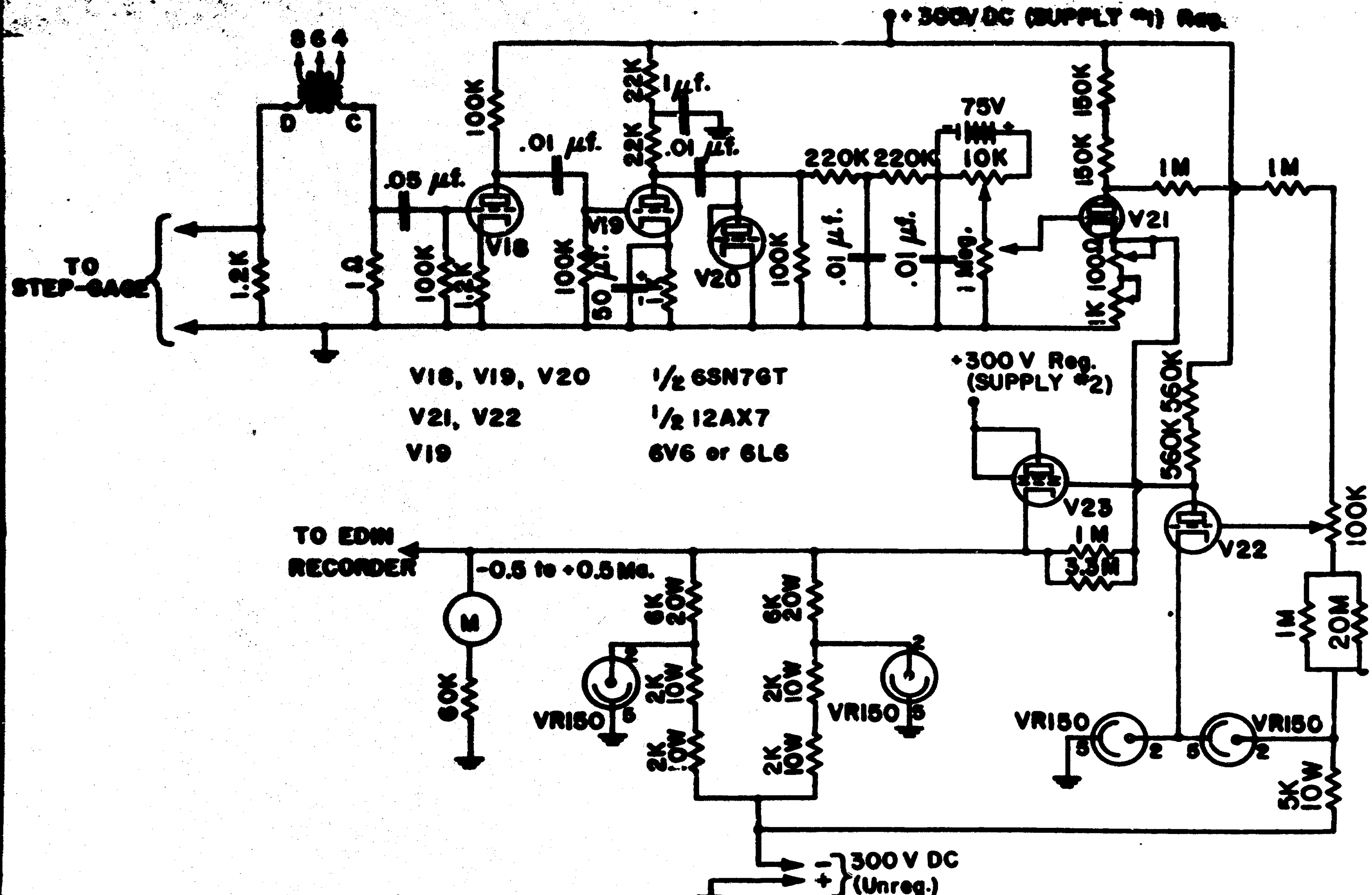
FIGURE 37

where N is the number of immersed electrodes. Now since V and I are proportionally related ($V = R_s I$) and since water depth is stepwise proportional to N ($h = 0.2\ N$, N an integer) then it is apparent that a recording of V(t) is also a step-recording of h(t).

To embody this theoretical basis of our measuring method, electronic means were utilized for recording V(t) and also for generating and regulating E. Figure 38 is the schematic of the amplifier designed for recording V(t) and includes two triode amplifying stages (V18 and V19) handling the 2000 cycle signal, a rectifier V20, and D-C amplifier triodes V21, V22, and V23. The last stage, V23, is connected as a cathode follower and is required to be rather powerful in order to drive the Edin recording galvanometer. No separate D-C amplifier was used with the step gage. Generator E (Figure 34) was actually the same unit used to energize the continuous wave gage, and terminals C and D of the output transformer were used for this purpose.

It will have been observed earlier in this report that the step gage recordings have a staircase appearance which becomes quite prominent for the very small wave amplitudes. This is not otherwise troublesome and in exchange, one obtains the very desirable feature that the stepped record may at any time be converted to terms of wave height simply by counting the number of steps in a given height interval and dividing by 5. Further, if this is done for some quite well-defined interval, say from a trough up to a crest, and the same interval is then identified on the record drawn by the continuous recorder, we are then in possession of the necessary calibration data with which the continuous gage recording may be translated into terms of ocean wave height. This calibration feature is a nearly ideal one, and even if the step gage records were of limited value in themselves, they would be very much worth their cost simply in the role of a calibration chart for the continuous-wire wave gage. Since the operation of the gage requires an insulator between the electrode and the mast to insure a water path for the current, water films remaining on the insulators after the water level has fallen will introduce leakage currents and resulting non-linearities in the calibration of the recording. An effort was made to minimize the effects of such films by adding a neoprene paint and a silicone grease water repellant (Dow Corning-4) coating to the insulators and the mast down to the level of the bottom electrode. That the problem was not completely resolved is evidenced by the fact that the step function in the recording is shown only when the water rises past an electrode; the slower time of water runoff in the case of falling water level smooths the step function.

A calibrator for the step-type wave recorder was constructed along the same general lines as described previously for the continuous recorder. That is, the step-gage with its 71 resistors, together with the 2300-foot sea cable, were simulated by an electrical network with adjustable elements to duplicate the effect of various water levels. This simulator checked out fairly well when self-calibrated recordings were later made available for comparison, although some minor discrepancies were found. But its greatest value, however, was in the early developmental stages during which it served as a very useful substitute for the



STEP GAGE AMPLIFIER

FIGURE 38

sea installation, which was not available at that time. The latter, in fact, was not available for tests until some time after the electronic equipment had been designed, constructed, and tested.

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